DOCTORAL DISSERTATION

学位論文要旨

A NOVEL TECHNIQUE OF OPTICAL FREQUENCY SWEEP LINEARIZATION OF A DFB LASER FOR HIGH RESOLUTION FMCW REFLECTOMETRY

高分解能 FMCW リフレクトメトリのための DFB レーザの光周波数掃引の線形化

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ABSTRACT

Frequency-modulated continuous-wave (FMCW) interferometry has become a more popular technique in recent years and is being widely used in optical ranging measurements. In an ideal system, the optical frequency sweep of the laser occurs linearly and periodically in time resulting in a constant beat frequency in time, in which the information regarding the distance can be extracted after FFT analysis. However, the system is suffering from nonlinear of the beat frequency. The linearity of beat frequency is affected by the nonlinearity of sweep frequency of DFB laser diode due to nonlinear optical frequency change against injection current. Internal modulation by current injection of sweep frequency in most cases is nonlinear. Nonlinear effects in optical beat frequency can severely degrade the accuracy of the measurement system since it causes the spectrum to smear, making it hard to determine the target range and range resolution. Nonlinear optical frequency sweep has become a challenging issue in the research topic to be solved recently. Continuous research is kept going to ensure the system achieve the highest linearity in beat frequency directly and accuracy in range measurement wholly. In this report, we proposed a linearization method by modifying the frequency modulation (FM) waveform through the external sampling technique to reduce the effect of nonlinear optical sweep frequency. In this technique, the triangle modulation signal is externally sample with the non-equal interval clock pulses generated from the nonlinear interference beat signal and is then analyzed using Fast Fourier Transform (FFT). External sampling clock where temporal sampling will coincide with the interference beat signal caused the shape of triangle waveform will be slightly curved and distorted. Tiny deterioration at the turning point of triangular modulation waveform was obtained. As a result, the sampled waveform is slightly distorted compared to the original modulating waveform. After the sampling process had occurred, one-period interval of the modified sampled FM triangular signal was extracted and was used to reconstruct a new FM triangle signal using the software called waveform builder. At this point after sampling process occurs for the first time, the shape of the modulation waveform is seen to have tiny distortion at each of the turning points and is slightly curved compare to the original modulating waveform. Then using the waveform generator, the new constructed FM

triangular signal (with slight modification) was re-launched to the system. The processes were repeated until the beat frequency approached linearity. Through experimentation, the proposed linearization technique after the 2nd iteration sampling process proved that the technique effectively reduced the issue of nonlinearity in optical frequency sweep. Linear indicator estimation is used to validate the linearity improvement throughout the proposed method. Linearity reduction at 60% was accomplished from the first experiment. In this report, we also presented another study to achieve better resolution on frequency interval of the beat spectrum. It is proved that the best combination of repetition frequency and modulation amplitude, together with skip function and zero adding technique in FFT analysis can sharpen the frequency spectrum which contributes to range measurement system's accuracy. The spectrum purification is evaluated using FWHM concept where 66% improvement in frequency interval was achieved. The proposed methods above are a very promising method to linearize optical frequency sweep and, as a result, to enhance the spatial resolution of FMCW sensing system.

LSIT OF FIGURES

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ABBREVIATION

ADC	Analog to digital converter
BS	Beam splitter
DC	Direct current
DFB	Distributed feedback
DFB-LD	Distributed feedback laser diode
DFT	Discrete Fourier transform
DUT	Device under test
FFT	Fast Fourier Transform
FUT	Fiber under test
FMCW	Frequency modulated continuous wave
FWHM	Full width half maximum
I	Injection current
OCDR	Optical coherence domain reflectometer
OFDR	Optical frequency domain reflectometer
OLCR	Optical low-coherence reflectometer
OTDR	Optical time domain reflectometer
PD	Photodiode
V	Voltage

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

We are very fortunate to be in the era where technology is moving fast along time. The extraordinary achievement that we have received today is owed to the noble breakthroughs, new discoveries, and the invention of continuous research accomplished by scientist and expertise around the world. Communication technology, for example, has moved the world to the next dimension that is far beyond our mind. As antenna and radar satellite communication always champions in connecting the world [1][2], In recent years, adopted from these technologies, optical network has emerged as one of the most popular and very useful communication technology. The use of fiber optics has become very common in a long range communication system. Among the famous usage of an optic-based apparatus is non-contact sensing technique. Optical techniques used in measuring target distance have a large range of applications. This interferometry technique is being employed for its fast and automated measurement in both very long or short distance [3][4]. The adeptness of interferometry in utilizing the wavelength of light as a basis for measurement and later to transform the constituent of wavelength into numerical data has made optical interferometry an invaluable tool for precision measurements.

We are very fortunate to be in the era where technology is moving fast along time. In this research, we report the non-contact optical measuring techniques that worked on measuring distances, and we restrict our attention to optical FMCW interferometry. Optical FMCW interferometry for remote distance measurement is found to be very valuable for its ability to be used wherever contactless and robust evaluation is required and other advantages mentioned earlier. In an ideal system, the sweep frequency of the laser occurs linearly and periodically in time resulting in a linear beat frequency in which the information regarding the distance can be extracted after FFT analysis [5].

However, practically, linearity in a sweep frequency ramp is difficult to obtain, and this leads to a nonlinear beat frequency. Nonlinear beat frequency has become a challenging issue in the research topic recently. In most cases, the beat frequency is fluctuated in time because of nonlinearity in the optical frequency sweep due to sweeping speed inconsistency in laser diode behind the injection current change. Fluctuation of the beat frequency will degrade the precision of the ranging since it causes the spectrum to broaden, making it hard to determine the distance to the target and the spatial resolution. Broadening of the beat spectrum is caused by fluctuation of the beat frequency. Conversely, if the optical frequency is linearly swept, a constant beat frequency is obtained and the distance to the target can be accurately extracted.

To date, scholars around the world are still in research to address the longtime issue of nonlinear frequency swept of DFB laser in optical FMCW. In this research, we propose a noble technique that successfully overcome the issue of nonlinear beat frequency and review other related parameters such as beat frequency spectrum and spatial resolution. The proposed linearization technique has been worked out through experimentation, and the result showed this method effectively reduced the issue of nonlinear optical frequency sweep and efficiently improve the interferometry system's accuracy. The technique will be described further in the later chapter, stressing every foundation of each constituent, guiding to a comprehending of its merits and weaknesses, performance and limitations.

In this research, we proposed a sweep frequency of DFB laser linearization method by modulation waveform optimization for high-resolution FMCW interferometry. In brief, we modified the frequency modulation (FM) waveform through the external sampling technique to reduce the effect of nonlinear beat frequency. In this technique, triangle-wave FM sweep is generated from a DFB laser source and transmitted through the system and re-sampled by the Analog Digital Converter at the external sampling rate (temporal sampling). As temporal sampling changed with time, this resulted in a tiny deterioration in the FM waveform at the beginning of each ramp. Thus, a pre-distorted FM waveform was obtained. One period interval of that distorted FM waveform was extracted and used to reconstruct a new FM waveform signal. This newly constructed signal was later retransmitted to the system as a new FM sweep signal. The process was repeated until the linearity of the beat frequency was noticeably improved. The proposed technique of sweep frequency linearization has been carried out through experimentation, and after the 2nd iteration, the result showed that this technique efficiently reduced the issue of nonlinear beat frequency.

While concentrating on correcting the system nonlinearity, attractively, throughout the experiment we discovered something no less important that contribute to better accuracy higher resolution of FMCW sensing technique. Proper selection of certain parameters during FFT analysis can sharpen the frequency spectrum which contributes to higher resolution. Thus, second involvement in this work is paying close attention to other criteria and parameters during the experiment that are important in improving the whole system to a considerable degree of preciseness.

1.2 RESEARCH GAP

1.2.1 Nonlinear Issue

Linear sweep of DFB laser in Optical FMCW interferometry contribute to the capability of obtaining high precision beat frequency measurements and high-resolution range measurements. Precision range data are beneficial to the interferometry system accuracy and accountability wholly.

The beat signal of the interference waveform will persevere constantly as long as the sweeping speed of DFB laser is absolutely linear. It shows that the measurement triggers at time and frequency domain will be both intermediate. Thus, no auxiliary interferometer for external clocking is needed. Unfortunately, up-to-date no lasers can sweep perfectly linear, therefore, the system is suffering from nonlinear of the beat frequency. The linearity of beat frequency is affected by linearity of sweep frequency of laser diode. Internal modulation by current injection of sweep frequency in most cases is nonlinear. Nonlinear effects in optical beat frequency can severely degrade the accuracy of the measurement system since it causes the spectrum to smear, making it hard to determine the target range and range resolution. Continuous research is kept going to ensure the system achieve the highest linearity in beat frequency directly and accuracy in range measurement wholly.

1.3 THESIS OBJECTIVES

To overcome the issues mentioned in previous sub-chapter above, therefore, the absolute goal of this study are:

1. To achieve linearity in the beat frequency of optical frequency sweep linearization of a DFB laser for high precision of FMCW reflectometry

2. To achieve high resolution of FMCW sensing system through modulation waveform optimization

1.4 MOTIVATION

With recent advancement in both laser and fiber optic components, new opportunity in non-contact sensing and distance measurement has become a realization. By using a compatible tunable laser diode and fiber components, range or distance measuring system can be performed utilizing an intelligent technique found; frequency modulated continuous wave (FMCW) [6][7][8][9].

Optical interferometry becomes most adopted technology owed to its non-contact and robust characteristic especially for distance measurement. Moreover, their physical principle allows the operation on linear measurement with a higher accuracy of below the nanometer.

1.4.1 Motivation and previous work

The motivation behind the research to address the linearity issue in Optical FMCW interferometry comes from the ability and effectiveness of the system itself. The are many characteristic of Optical FMCW interferometers that makes thus technology worthily explored [10] :

- Optical FMCW is usually used in measuring a stable or quasi-stable condition which means the output will be at particular stable/half stable for pre-determined period of time after that it will bounce back to its original source so that the information from the frequency and phase can be extracted in calculating the beat signal.

- It has the important capability in the case of power interruption where the particular information required to measure the range distance can be recovered
- Optical FMCW interference as compared to the traditional optical interference offers a higher accuracy and longer distance measurements due to its dynamic signal transmitted in a continuous function of time that gives higher resolution
- FMCW interferometer in fiber-optic is very beneficial in terms of its ability to interconnect between the fiber-optics networks to form multiplexed fiber-optic interferometers. This is very helpful since a single light source and a photo detector can measure multiple targets simultaneously.
- FMCW optical interferometry offers a compact, reliable, flexible and more accurate in advanced detection techniques.

The drawbacks of fluctuated beat frequency have been widely discussed and many efforts have been made to overcome the issue. Continuous research and studies are kept going to ensure the system achieved the highest linearity in beat frequency directly and accuracy in range measurement system wholly. For example, Minho Song and Shizhuo Yin [11] made a “robust and compact design of the optical frequency discriminator”, Koichi Iiyama discussed on the adaptation of Voltage Controlled Oscillator (VCO) [12] and Soo-Yong Jung adopt “an additional fixed delay structure to extract the nonlinearity and compensate it” in his work [13]

1.5 THESIS OUTLINE

The main contribution in this research is establishing a system with higher accuracy, stability and is precisely operated tools in measuring distance especially in optical fiber networks. A linear beat frequency of optical FMCW interferometry ranging technique in accomplishing the foremost goal of this Ph.D. masterpiece that is to achieve the highest precision in distance object profiling measurement. An optical interferometer in FMCW techniques has proven to be the most efficient and effectual tools in range measurement for its higher accuracy and resolution. Nevertheless, the drawback to its popular demand is nonlinear [5][14]. While tons of experiments conducted in achieving the ultimate goal, it is found that, selection of parameters is important to achieve the optimum results.

Chapter 1 briefly explains the whole idea of this thesis, while chapter 2 describes the theoretical framework of the technology adopted in this experiment work. This chapter also reviews the earlier technologies that have been employed in noncontact sensing techniques and deliberate the advantages of different interferometry system for a specific application. In chapter 2, we discussed three techniques that adopt the intensity-based LASER technology namely, time-of-flight, phase-shift technique and interferometry system. We also review three most popular reflectometry techniques, i.e. OTDR, OLCR and OFDR. All of these measurement systems have been integrated into commercially available. Next we discuss specifically on optical FMCW interferometry system.

Chapter 3 presents the noble technique in addressing the issue on a nonlinear effect that the system is facing. With the purpose of linearizing the optical sweep frequency of DFB laser, we adopt a noble technique of modulation waveform. The modulation waveform is sampled with the sampling signal generated from an interferometer, and then a laser diode is modulated with the sampled waveform.

Extension from the previous chapter, chapter 4 separately discuss the parameters that affecting the sharpness of beat spectrum for higher resolution such as value selected for both modulation amplitude and repetition frequency.

In the final sections, chapter 5, we will discuss and summarize based on the results which have been presented in international journals the outcomes and present state of the work from this research and proposes recommendations for upcoming research that could continue to advance the state of linearity in optical FMCW interferometry

CHAPTER 2

OPTICAL FMCW INTERFEROMETRY

2.1 INTRODUCTION

One of the very significant factor that can't be denied which facilitate optical interferometry technology is a realization is massive growth of LASER technology that is constantly evolving. To cope with the massive growth of this technology, a great demand on the measurement tools or interferometry to ensure the stability of this system. Fiber lasers are emerging as attractive alternative technologies due to its excellent ability in amplifying properties, ease of modulation and large bandwidth for optical interferometry system. Over the period, laser diode pumps have become matured and are reliable for its robustness, also the readiness of their compatibility with the fiber-optic devices along the transmission medium. In addition, a major key point is the ability to emit continuous wave constantly [15][16]. This explains why interferometry technique started to be more implemented after the LASER sources technology became available.[17][18][19][20][21].

In the non-contact sensing technique, some methods demand continuous light sources while other practices use a light pulse sources. Likewise, some methods demand highly coherent and fine bandwidth light while others can just operate using incoherent light. The first and one of the simpler types in intensity-based non-contact sensing for measuring target range comprise of a light source and a detector, where the light intensity emits from the light source (laser diode) transmit through an optical fiber medium and reflected from the target onto the detector. The information on the distance between the target and detector is then can be extracted and. Non-contact sensing technique has been commercially available for more than 40 years [4][22].

2.1.1 Laser ranging technique

Attributable to its compactness, low-cost and ease of modulation laser diodes are very popular in laser ranging technique. Laser ranging technique employed in non-contact optical sensing techniques provide the valuable capability in measuring the target distances and other related applications for instance object displacements, velocities, surface object profiles, and 3D vision [23][24][17]. The most precise linear distance measurements are executed thus far by means of laser interferometers [25].

Research in distance measurement or linear displacement measurement is a very valuable study and it offers a large number of solutions. In overall there are many different optical techniques with different capability in measuring distance, for instance, intensity-based, time-of-flight, triangulation, interferometry sensors, and other techniques as shown in figure 2-1[4]. Conventionally, there are three techniques that are most considered and well-accepted as major techniques for a non-contact sensing technique using laser rangefinder namely the time of flight, multiple frequency phase-shift and interferometry.

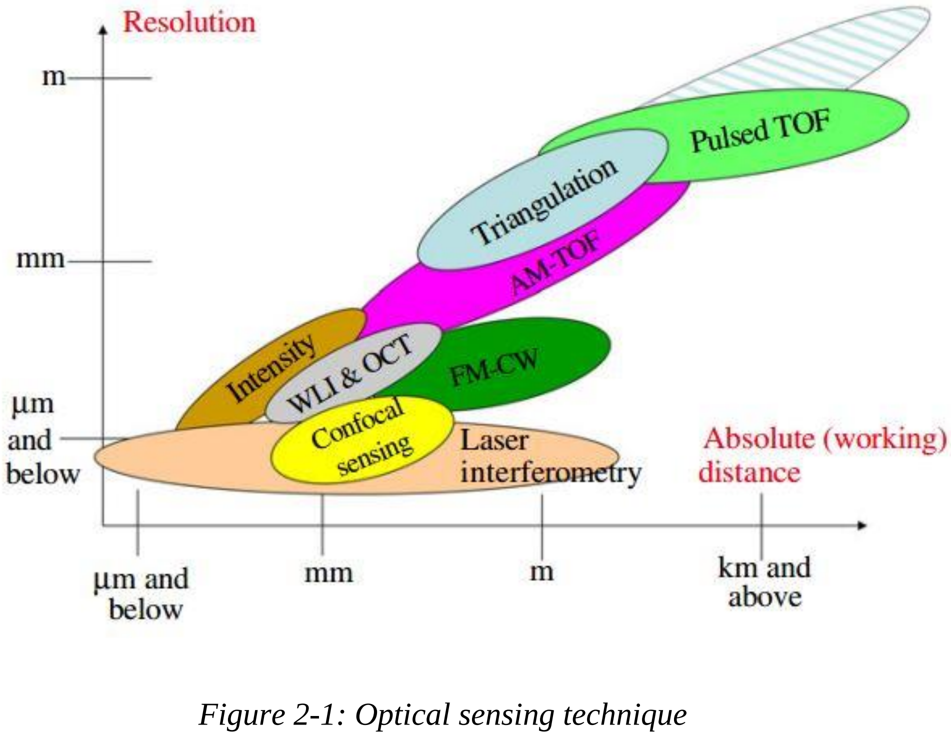

Figure 2-1: Optical sensing technique

Time of flight – this technique has been comprehensively used for manufacturing assessment in recent years. The principle of this techniques based on semiconductor laser diodes operates by transmitting a narrow beam laser pulses onto the target object. The pulses are sending sequentially and the time taken for the pulse to be reflected from the target object to the source has the information that can be extracted and calculated to determine the distance. This technique demands a rigid timing circuitry (sub-nanosecond). Since the distance is determined by calculating the round trip time of the optical pulse signal, and this technique promise a good performance with high signal to noise (SNR) ratio. Nevertheless, due to the high speed of light is employed; this technique is not suitable for high accuracy measurements (sub-millimeter), where other techniques are preferable to be used. Moreover, this method required high cost [26].

Multiple frequency phase-shifts – is an extended approach to TOF method by substituting the light pulse to continuous amplitude modulated wave. It is a good technique for obtaining a resolution for millimeters from 1meter up to 50 meters non-contact range (a few times larger than TOF using pulse light). In this technique, the optical power is modulated in a sinusoidal fashion with a constant frequency. After reflection from the target, a photodiode collects the time information on reflected sine wave and the round-trip time is turned into phase shift. The phase shifts are realized by establishing phase delay between the two RF signals. In another word, it measures the phase shift of multiple frequencies on reflection then work out some simultaneous calculation to determine the distance. Concisely, using phase difference between the reference and reflected signals, the distances can be determined [27] [28].

The technique provides non-complex yet low-cost laser-distance measurement tools. Although it is the most practical method for measuring a distance from 1 meter up to 50 meters, it faces a difficulty for distance less than 1 meter because it requires a gigahertz range modulation rate for measuring shorter distance. It also experiences the disadvantages from great phase faults that propagating throughout the signal. In addition, it is difficult to demodulate the phases perfectly when the non-contact target shells have disjointedness [29]. Moreover, the limitations such as intermediate frequency drift and high level of the photoelectric signal [30] [31] [32].

FMCW Interferometry – is a measuring technique that uses the phenomenon of wave interference (typically an electromagnetic) in extracting the information.

Interferometers are used in many applications but are most accurate and most useful technique for measuring absolute distances [25]. It is also an alternative approach of pulse TOF in which instead of using pulse, FMCW interferometry, for instance using continuous wave of modulated frequency. There are few types of interferometers known for potential such as Michelson interferometer, Mach-Zehnder interferometer and Fabry-Perot interferometer [10].

An optical interferometry which also has its origin in radar applications is mostly used in many conditions that demand high resolution and precision in measuring short distance or very small linear displacements. It operates based on the superimposed phenomenon in which two or more light waves meet and produce interference. Generally, two categories of radar systems used in distance measurement known as time-domain and frequency domain. In time-domain, a series of pulses are transmitted and the time delay is measured of the return pulse. The time delay of the transmitted pulse is conforming to target distance. The necessity to get a very accurate length of time interval makes it hard to obtain the position of the object precisely because a highly accurate and precise clock signal and high-speed detection circuit is compulsory to achieved higher resolution. To overcome the issue, the technique of continuous wave is introduced where time measurement is replaced with beat frequency measurements. Conversely, the frequency-domain system uses frequency modulated wave signal to measure the distance using the frequency difference between the transmitted signals and reflected signals. The detection processes are simpler because the frequency difference is as low as tens of megahertz [32].

The fundamental concept of optical interferometry was first discovered by Albert A. Michelson around 1880 when he detected possible changes is the speed of light while conducting an experiment to explain the light propagation using a partial mirror to generate interference [27].

The principle of optical interferometry (Michelson interferometer) is shown in Fig. 2-2. In basic Michelson operation, a laser light propagates through a beam splitter, with one of the laser light travels towards a fixed mirror. Meanwhile, another laser light propagates towards the target distance. The reflected signal from both mirrors is combined and the intensity pattern developed at the detector is captured. Intensity changes give the info on the phase difference between the two beams and provides a measurement of distance [28].

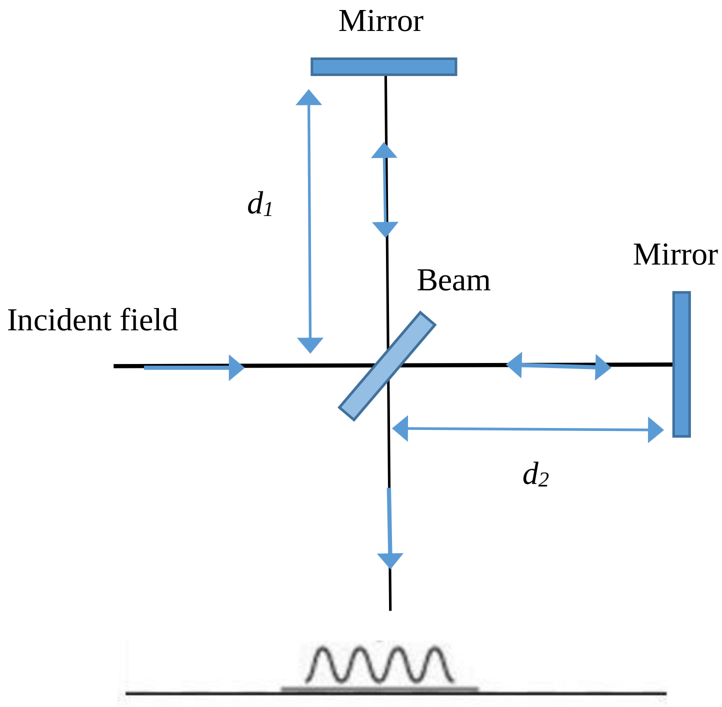

Figure 2-2: Basic configuration of optical Michelson interferometry

In an FMCW interferometry, a continuous sinusoidal wave signal with a constant rate of frequency change is transmitted and is reflected by the target. The beat frequency can be calculated using the information extracted from the frequency difference between the transmitted signal and the backscattered signals received. For a linear frequency sweep, the distance data accurately obtained because the beat frequency is focused at a single frequency.

2.1.2 Reflectometry Technique

Absolute distance measurement in optical range finder is of great demand in many industrial applications especially in conducting nondestructive testing, non-contact distance measurements or predictive maintenance. In non-contact range finder, an electromagnetic signal such as radio, ultrasonic or optical is launched towards a target and the reflected signal will produce interference phenomenon at the detector where the distance can be determined accurately [29][30].

In optical reflectometry, the used of a laser as in measuring distance is very significant and is benefitted three important techniques; Optical Time Domain Reflectometry (OTDR), Optical Low-Coherent Reflectometry (OCLR) and Optical Frequency Domain Reflectometry (OFDR) [31][32][33]. All three techniques offer different weights in distance range (from few mm to km), resolution, speed, sensitivity and accuracy from less to the most responsive and accurate measurements. The advantages of coherent reflectometry techniques can't be denied.

OTDR: Optical Time Domain Reflectometry (OTDR) was first demonstrated 50 years ago and is well-recognized for its competency in maintaining fiber optics networks. This technique has become a benchmark for describing the loss and failure in short or long haul optical fibers [34] [35] [36][37][38][39].

The basic idea of OTDR is the ability to characterize the reflected signal from Rayleigh backscattering throughout the fiber networks. Among the value points of this technique in measuring fiber attenuation and loss, locating the imperfection of the fiber up to several kilometers, this back distance measurement has an important advantage which it requires only one end access to perform the test. This is a very significant support to nondestructive measurements. The fundamental principle of OTDR is measuring the time of the incident short light pulse and the amplitude of reflected pulse. A very short light pulse is launched into optical fiber network, and the wave shape of backscattered light is measured. Generally, an ideal OTDR system would give the useful information on fiber characteristic on distributed fiber networks [40][41] [42].

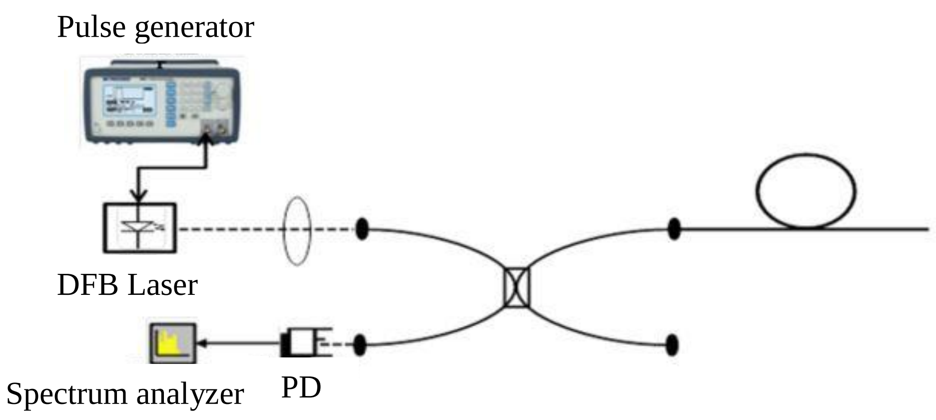

Figure 2-3: OTDR system configuration

Despite all the advantages, this technique however, has some disadvantages such as inaccurate loss values, low signal to noise value in single mode fiber using laser diode source that limits the length that can be measured. Since this technique is probed with a very short light pulse, in order to improve the spatial resolution, very shorter pulses need to be launched to increase the bandwidth. This will increase the noise level as well, thus reduces dynamic range indirectly.

OCLR: Optical low-coherence reflectometry (OLCR) is another measurement technique that is rapidly advancing in a measurement of small, closely spaced optical reflections with higher spatial resolution as small as 1.9 pm [43][44]. This technique has proven to have higher spatial resolution and detection sensitivity compared to OTDR. Having advantages for its excellent spatial resolution, OLCR is very useful in OCT (bio-medical usage) to deliver high-resolution 3D images. In addition, it is also beneficial for non-contact yet non-destructive measurements [45]. Fundamentally, in characterizing the optical reflection, OLCR uses low-coherence wideband light source and tunable optical delay that is spilt consistently between reference and target path. The reflected signals from both reference and target path are combined at photodiode and useful information on distance can be extracted. Regardless of all its advantages, to date, many reports on OLCR were not satisfied on the limited measurement ranges [43] [46]. Typically, the measurement range is restricted to less than 1m. To compensate with a larger range, the system need robust and compact devices. [47]

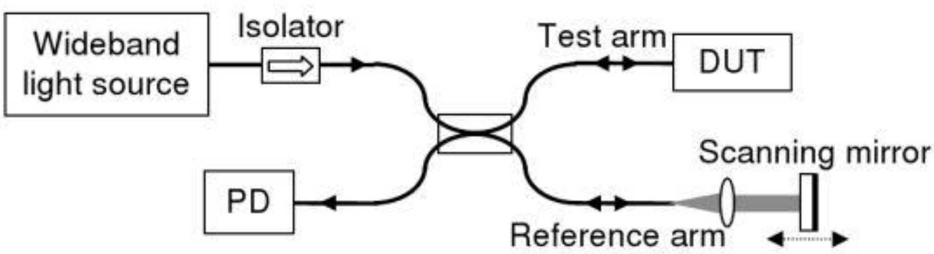

Figure 2-4: OLCR system configuration

OFDR: Optical frequency-domain reflectometry (OFDR) has been popularly known for its advantages in providing high sensitivity and frequency resolution (high spatial resolution - mm) and its great precision in many applications such as detecting, localizing, and diagnosing optical fiber since 1980 [48][49][50][51]. OFDR is suitable in short, medium and long measurement ranges with a spatial resolution of 50 mm has been reported [9].

OFDR operates by sending a frequency modulated continuous wave signal through measurement and is split into two arms; reference and target arm. The reflected frequencies from both arms are collected at photodiode caused the occurrence of interference. The interference which occurs in the spectral domain can be later transformed in time domain using FFT analysis and is measured for distance [52][53][54]

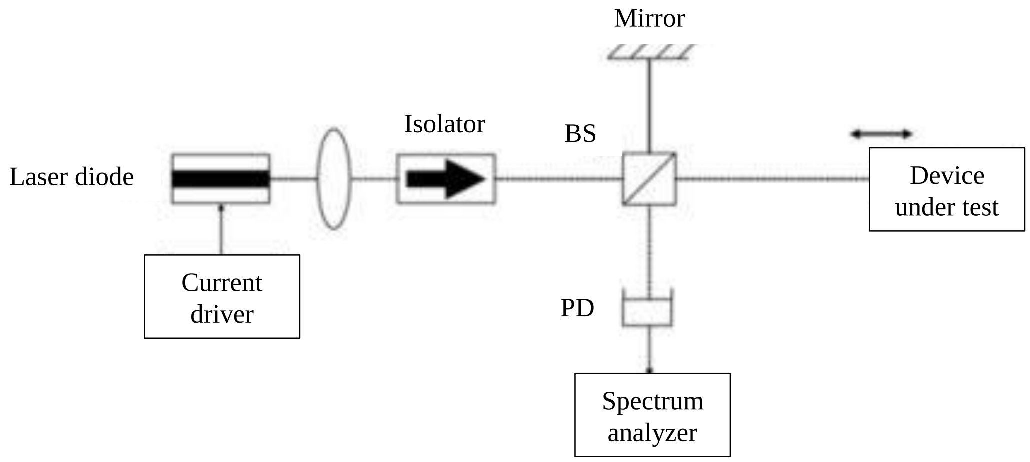

Figure 2-5: OFDR system configuration

In conclusion, OTDR is using very short pulse and rather complicated technique used for longer range yet low-resolution (reported from a meter to tens of meters) , then a simpler approach OLCR was worked for the improvement of OTDR using low-coherence technique with higher resolution (micrometer) and better sensitivity. However its measurement ranges are limited up to several meters only. Thus, its application is restricted to OCT field. In addition, it's facing a dispersion problem that lead to intense deteriorating to spatial resolution. This was solved by alternative technique OFDR that based on swept wavelength interferometry which has high spatial resolution and large measurement range.

Thus, OFDR is filling the gap between OTDR and OLCR. It also falls between OTDR and OLCR in range capabilities with millimeter-range resolution. OFDR also can be operated in both spectral and time domain and this technique is well-suited for intermediate length ranges measurement and has been demonstrated to show its capability in making smooth transition between OTDR and OLCR technique[47][55][56] [57] [58][59][60]

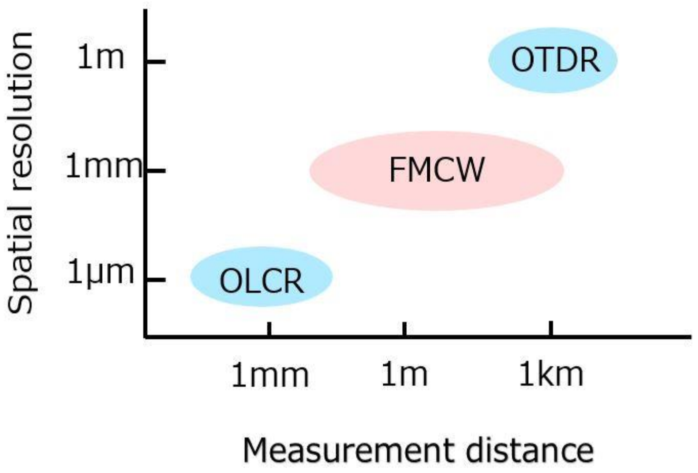

Figure 2-6: Reflectometry techniques properties

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Reflectometry technique	**Measureable distance**	**Spatial resolution**	**System configuration**
OTDR	Very far (km)	Not good (meter to tens of meters)	Moderate
OLCR	Very short (mm)	Very good (micrometer)	Moderate
FMCW	Moderate (meters to kilometers)	Moderate (millimeter range)	moderate

Table 1: Comparison OTDR, OFDR, OLCR

2.2 PRINCIPLE OF FMCW INTERFEROMETRY

The concept of FMCW interference was firstly explored in radar last 50 years ago and has been introduced to optic science in the early 1980s when the precision time domain reflectometry OTDR was discovered [61][62][63][64][65][66]. It is known as FMCW radar.

Radar technology has contributed huge opportunities to modern communication and has greatly benefitted all humankind. In radar concept, primarily the radar transmits extremely high power of short radio pulse. These pulses propagate in the direction directed by the antenna with the speed of light. If there is an obstacle in this direction, then the energy of the short radio pulse transmitted will be scattered in all directions including those that reflected back to the radar. The receiving antenna receives this energy and evaluates the contained data. Echoes (energy that reflected back to the radar) later are combined with the transmitted signal of radio pulse to form a beat signal where the target distance/range can be extracted after unwrapping process.

In general, there are two types of radar that are popularly used in ranging measurement and detection; time-domain and frequency domain. In time domain radar, the time delay between the series of incidence pulse and the reflected pulse is measured. This temporal delay is proportional to target distance. In order to get precise location or position of the target object and higher resolution, extremely accurate system with rigid clock signal and high-speed circuit is a necessary.

In resolving the issue, the latter technique using frequency domain proposed. The time measurement is substituted with beat frequency measurement after the technique using continuous wave is presented. In contrast to earlier techniques, frequency-domain radar technique transmits frequency modulated continuous wave (FMCW) signal to the target object and the distance can be elucidated by calculating the frequency difference between the transmitted signals and reflected signals. FMCW radar offers a simpler process in detection and ranging because the system operates at a lower frequency that is as low as tens of megahertz. As the technology advanced, FMCW radar has become well-accepted for their advantages especially for higher resolution measurement, or in measuring short distance also tiny linear displacements.

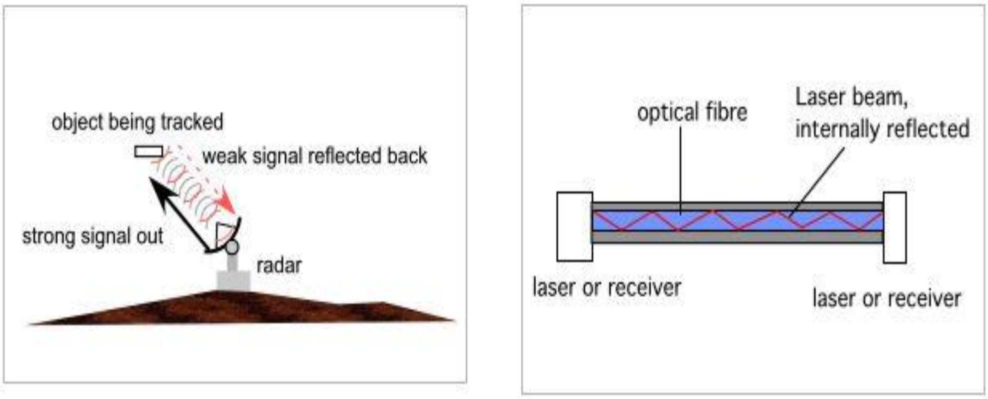

Figure 2-7: Optical FMCW originated from FMCW radar

In FMCW radar, a narrow-bandwidth continuous wave signal is modulated with constant amplitude and transmitted towards target object by transmitting antenna. The frequency of the signal is varied in sawtooth or triangle wave fashion and is first split into two waves, reference and reflected wave which travel along different paths and then interfere. The reflected wave signal (echo) received at receiving antenna will mix with the reference wave at the mixer (e.g. diode detector) and the beat note which contain the frequency difference is collected for further calculation [66].

Originate from continuous wave FMCW radar, optical FMCW adopted this reflectometry concept with the use of laser source for generating linear swept light-wave frequency to be transmitted towards target [67]. As FMCW radar uses air space as a transmission medium, optical FMCW radar using optical fiber for transmission. Optical FMCW radar operates based on Rayleigh Backscattered and Fresnel concept while FMCW radar works on Doppler Effect. The beat frequency is identified when interference occurs between the backscatters light and reference light at photodetector. A very high coherent light-wave source is required for longer range distance measurements.

Besides its absolute measurement advantages such as high resolution and large measurement range, it is also feasible and simpler technique that has been demonstrated to be efficiency in fiber optic properties. In addition, optical FMCW offer special ability where this system can be inter-opt with other interferometers such as Michelson FMCW, Mach-Zehnder FMCW and Fabry-Perot FMCW[10][68] [69][70].

The study on optical FMCW is to be of great important for its huge advantages in the area such as in spectroscopy and metrology [71].

2.2.1 Principle of operation

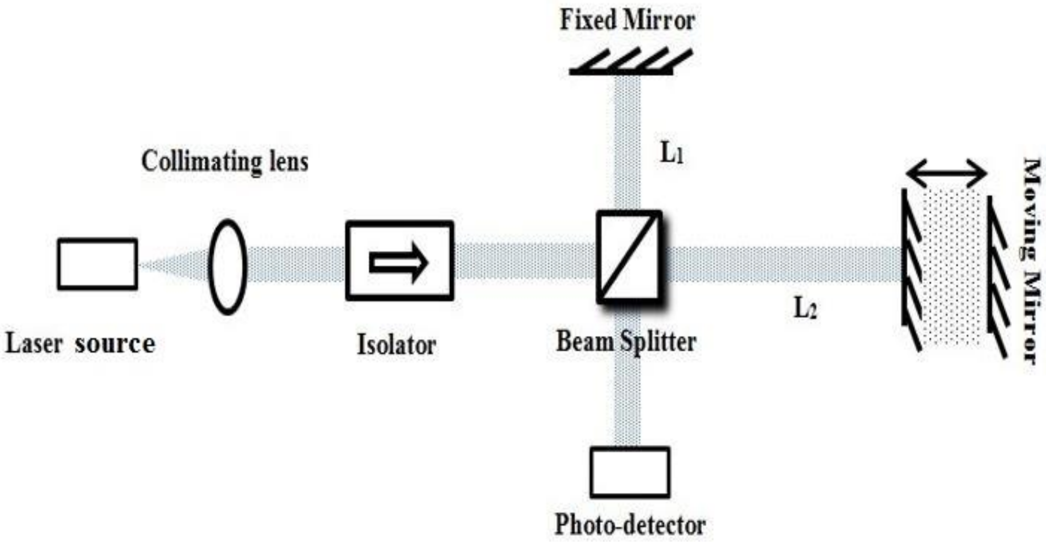

Figure 2-8: Basic configuration of optical FMCW interferometry

The basic configuration of optical FMCW interferometry has been developed resemble the classical parallel beam Michelson interferometer. However it differs from Michelson principle where, in optical FMCW frequency modulated laser semiconductor is a light source. Typically, the transmitter of optical communication system consists of a laser diode that is being modulated either directly or indirectly. A direct modulation of a laser is via the injection current while indirect modulation (also called external modulation) of a laser is via an optical modulator. The modulation signal can select any waveform fashion such as a sawtooth wave, a triangle wave, a sine wave or a square-wave, also can take a form of amplitude, phase or frequency modulation [72].

This system known for its simpler and easy operation consist of a laser semiconductor as a light wave source, a collimating lens to ensure parallel light entering the system, an isolator to maintain one-way transmission, beam splitter which split the incident laser beam into two difference paths and lengths; reference beam and another beam that lead to FUT (L_1 and L_2 respectively), two mirrors that attached to the end of the each arms, one is fixed while the other mirror can be moved for different length and a photo detector (photodiode) that collect the interference signal and converts lights into current.

A stable modulating frequency continuous wave that oscillate up and down alternately is transmitted through the system over a certain tempo. The longer the delay, the bigger the frequency difference between transmitted and received signals, hence the distance. A laser diode is always the best choice as a light source for transmitting a sweep frequency. A laser diode is modulated with a variety of modulation fashion such as sine-wave, sawtooth-wave, and triangle-wave and can take any form of amplitude, phase or frequency modulation.

In this scenario, the optical frequency of the semiconductor laser is temporally swept by triangle modulation waveform, and the interference signal appears known as a beat frequency is proportional to the optical path [73][12]. Therefore, the frequency of the distance distribution of the signal light can be observed. Thus, the position of the reflection from the measurement target in the FMCW optical sensor system is converted to the beat frequency, and it is topographically characterized the distance measured. Using a theoretical model, the measurement principle is described as in eq. (2-1) with c is the light speed in a vacuum. Having a time difference is given by τ, where both electric field of the reference beam E1 (t), and the signal beam E2 (t), arrived concurrently at Photodiode at time t, can be expressed as [74];

$$\begin{aligned} E1(t) &= E1e^{(j2\pi f1)} \\ E2(t) &= E2e^{(j2\pi f1)}.e^{(-j\delta)} \end{aligned} \qquad \textit{Eq. 2-1}$$

The above equation can be represented in phase difference δ as in eq. (2-2)

$$\delta = \frac{2\Delta D}{\lambda}.\, 2\pi \qquad \textit{Eq. 2-2}$$

Therefore, in this case, the intensity of the interference signal I (t) obtained at photodiode explain by eq. (2-3)

$$
\begin{aligned}
I(t) &\propto \big(E_1(t) + E_2(t)\big).\big(E_1^*(t) + E_2^*(t)\big) \\
&= E_1(t).E_1^*(t) + E_1(t).E_2^*(t) + E_2(t).E_1^*(t) + E_2(t).E_2^*(t) \\
&= E_1^2 + E_2^2 + 2E_1E_2\,cos[2\pi|f_1 - f_2|t - \delta] \\
&= E_1^2 + E_2^2 + 2E_1E_2\,cos[2\pi f_b\,t + \delta]
\end{aligned}
\qquad \textit{Eq. 2-3}
$$

Where,

$$\mathrm{f_b} = \mathrm{f_1} - \mathrm{f_2} \qquad \textit{Eq. 2-4}$$

The basis of coherent optical FMCW reflectometry operates on the frequency difference between the reflected signal and reference signal received at the photodetector; originating from the same linear swept source, which is known as a beat frequency. The optical frequency of a laser diode is swept with a triangular-shape modulation of the injection current, and the optical frequency-swept light is split into two paths by a beam splitter to a fixed mirror (known as a reference signal) and to the device under test (known as reflected signal). The reflected signal from the target object interferes with the reference signal from the fixed mirror. The frequencies of the reference and the reflected signals are different due to the temporal delay between the reference and the reflected signals. The longer the delays between reflected and the reference signal, the higher value of beat frequency. Thus, distance measurement can be carried out by measuring the frequency difference $\boldsymbol{f_b}$ (also known as beat frequency) between the reference and the reflected signal as in Figure 2-8 [75].

The beat signals that also represent the correlation between Rayleigh backscattered signal counter to the reference signal is Fourier transformed by a spectrum analyzer, where optical frequency domain response is converted into spatial information for beat spectrum trace. A spectral analysis contains a useful value of the beat signal that's carry the information that is proportional to distance [16].

2.2.2 Distance range measurement

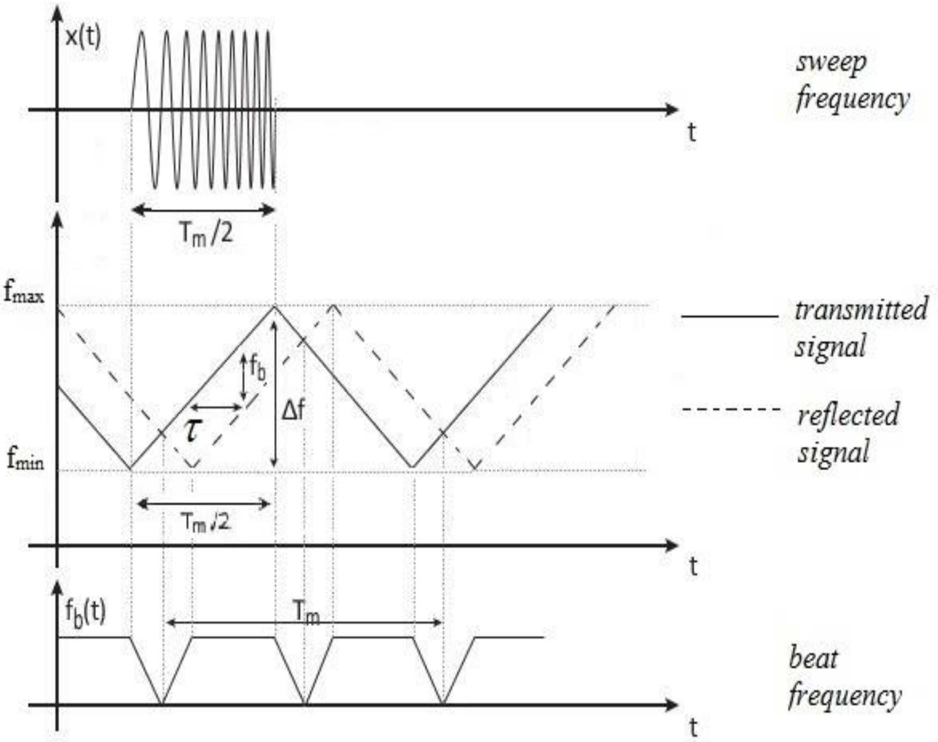

Figure 2-9: Optical FMCW

For a linear chirp sweep frequency, signal from a laser input propagates throughout the fiber, and split by the beam splitter into two paths with difference length that represent delay that correlating to its delay, after the reflected signal from both path recombined at beam splitter, the mixing output is done at photodiode (photodetector). The different time delays due to different length will cause two different frequencies which are called beat frequency f_b. Thus, distance measurement can be carried out by measuring the frequency difference f_b (also known as the beat frequency) between the reference and the reflected signal as in Fig. 2-8. The calculation of beat frequency f_b and the spatial resolution δz are given in this eq. (2-6) and eq. (2-7) respectively;

$$\frac{f_b}{\tau} = \frac{\Delta f}{T_m/2} \qquad \textit{Eq. 2-5}$$

$$f_b = 2 f_m \Delta f \times \tau \qquad \textit{Eq. 2-6}$$

$$\delta z = \frac{c}{2n\Delta f} \qquad \textit{Eq. 2-7}$$

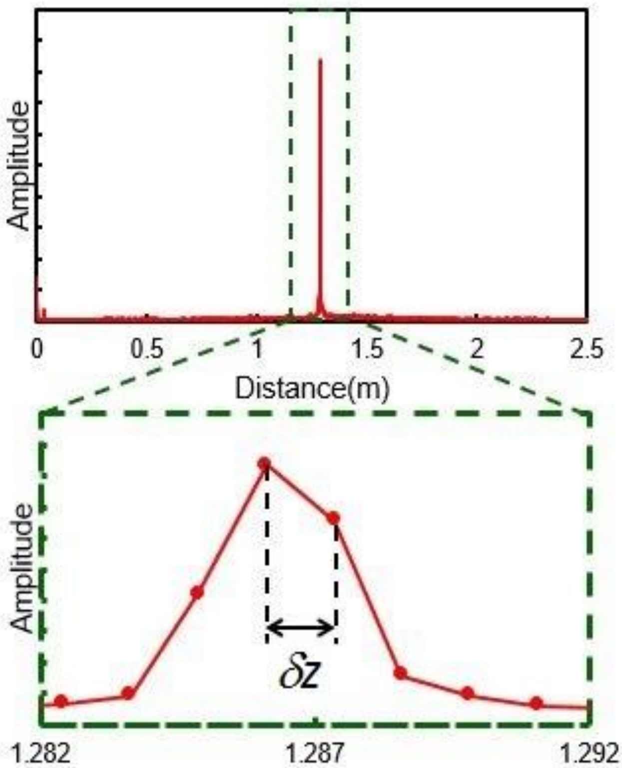

Figure 2-10: Spatial resolution

Theoretically, spatial resolution δz can be defined as eq. 2-7 with Δf is the sweep frequency bandwidth. From the equation, we know that spatial resolution is inversely proportional to the frequency sweep [53]. Thus, as the bandwidth of optical frequency sweep is increased, the resolution can be improved.

Fig 2-9 shows the spatial resolution of the beat spectrum. In the eq. (2-7), n is referring to the refractive index of fiber. In this case, n is 1.45. From the eq. (2-6) above and eq. (2-8), we can expand it to calculate the targeted distance d as in eq. (2-9), with fb representing the beat frequency that refers to the frequency difference between reflected signal from both path (reference arm and fiber under test), c is the speed of light which equals to 3×10^8 m/s [76], T_m is the period of a complete cycle of waveform signal which give maximum frequency deviation of f_m,. Δf in the above equation represents the bandwidth of the optical frequency sweep, and last but not least τ denotes the delay between reflected and reference signal due to the different length of both arms.

$$\tau = \frac{2d}{c} \qquad \textit{Eq. 2-8}$$

$$d = \frac{fb \times Tm \times c}{4 \times \Delta f} \qquad \textit{Eq. 2-9}$$

2.2.3 Spatial resolution

Spatial resolution is an important indicator in optical FMCW reflectometry. The signal is digitized by using an analog-to-digital (ADC) converter and undergone Fourier transform in order to convert the reference signal in the time domain into the frequency domain. The ideal spectrum for spatial resolution is when the spectrum is sharp with a single line width that equals to zero. Base on eq. (2-7), the ideal sharp spectrum can be obtained in a case where the optical frequency sweep width is infinitely large. As indicated in eq. (2-3), the interference signal is presented in the time domain. Analog-to-digital (ADC) converter digitized this interference signal for performing Fourier transform. . The spectrum in the frequency domain is obtained by time-variant (AC component) of a Fourier transform of the beat signal in cosine wave function as in eq. (2-10).

$$S(f_b) = 2E_1E_2\delta(f - f_0) \qquad \textit{Eq. 2-10}$$

Since the phase continuous duration of AC component is finite, the spectrum is widened. In the optical frequency sweep, with repetition frequency is f_m, the section where the optical frequency is swept linearly is, 0 ≦ t ≦ 1/2fm, the spectrum S(f') is

$$S(f_b') = S(f_b) \otimes sinc(2ffm) \qquad \textit{Eq. 2-11}$$

Here the ⊗ symbol represents the convolution integral. Spectrum is seen to have spread of sinc function, for sinc (x) = sin (x)/x. The spectrum width spread is shown in fig. 2.10 below. Fast Fourier transform (FFT) provides us with an alternative representation for discrete time (DT) sequences.

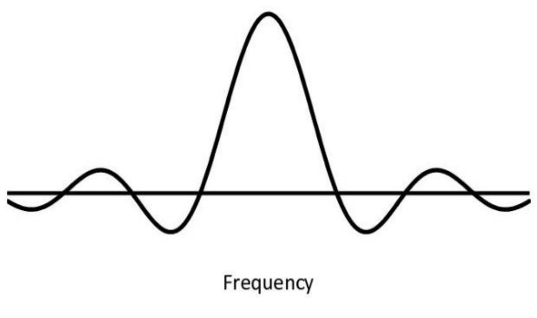

Figure 2-10: Spectrum width of the interference signal

In an ideal case, where the sweep frequency is linear, the value of beat frequency over delay, $\frac{f_b}{\tau}$ is constant everywhere. The constant effect of beat frequency contributes to a sharp spectrum of beat frequency because it allows the system to focus at a single frequency.

Conversely, in most cases, the beat frequency is inconstant. The fluctuation of the beat frequency caused by nonlinear sweep frequency owing to the nonlinear optical frequency changes against injection current. Fluctuation of beat frequency causes the spectrum to broaden thus, making it hard to focus at a single frequency. Indirectly it will affect the system accuracy since ambiguous in the system will degrade the performance.

2.3 NONLINEAR SWEEP FREQUENCY

The main issue of broadening spatial resolution of FMCW sensing is owing to the nonlinearity of sweep frequency. From the eq. (2-5) and (2-6), explained that the beat frequency is proportional to optical frequency rate. In this subchapter, we outline the factors and causes to nonlinear issue in sweep frequency of DFB laser diode.

The first reported used of FMCW sensing using TOF technique, disclosed the difficulties in achieving linearity $dv \,/\, dt$ since linear current modulating waveform did not yield linear sweep frequency modulation.

It is known that the modulation signal of a laser diode is very sensitive to the fluctuation of the optical frequency change against injection current and laser diode temperature. This will result in multiple values of beat frequency produced from the interference signal back-scattered. This leads to degradation of spatial resolution.

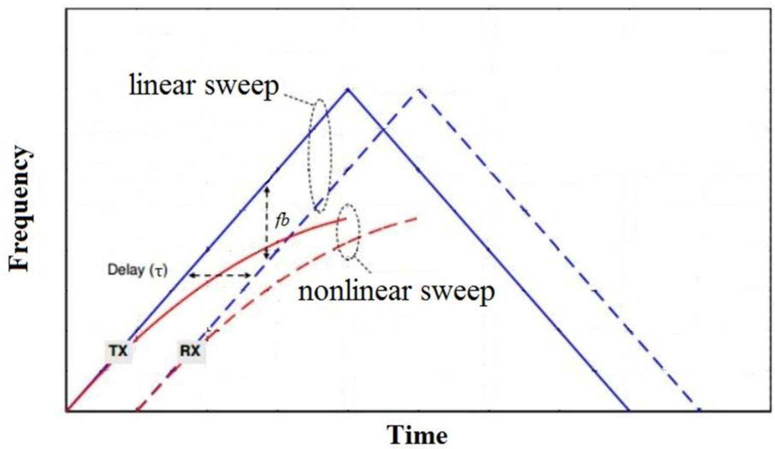

Figure 2-11: Inconstant beat frequency owing to nonlinear sweep frequency of DFB laser diode

In fig. 2-11, for an ideal system, the sweep frequency of the laser diode modulate linearly and periodically in time. Therefore, the beat frequency is constant everywhere and the accurate information on the distance range can be extracted after demodulation. On the other hand, in most cases, nonlinearity in sweep frequency ramp is occurred [77]. This leads to a nonlinear beat frequency. During the ramp of nonlinear sweep frequency, f_b**:** τ is not constant everywhere. As a result, the obtained information obtained contained a false answer. Linear beat frequency is shown in fig. 2-12 and Nonlinear beat frequency is displayed is fig. 2-13. In this fig. it can be seen that the rising and falling edge of the beat frequency also is different. This will be explaining again in the next chapter.

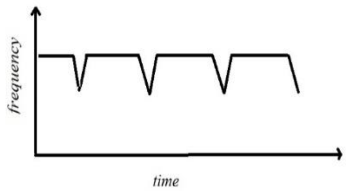

Figure 2-12: Linear beat frequency

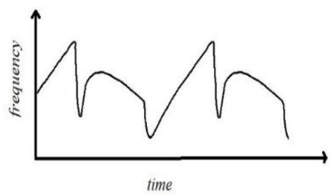

Figure 2-13: Nonlinear beat frequency

In the case where linearity in sweep frequency occurs, a constant beat frequency can be obtained as illustrated in fig. 2-14. Fourier transform on the beat frequency yields a sharp spectrum because the system can focus at a single beat frequency. Whereas, the spectrum is seen broaden once Fourier transform calculated onto inconstant beat frequency as in fig. 2-15. The fluctuations in beat frequency weaken the system capability to focus at a single frequency. Thus, the system is severely degraded and the target range is difficult to determine.

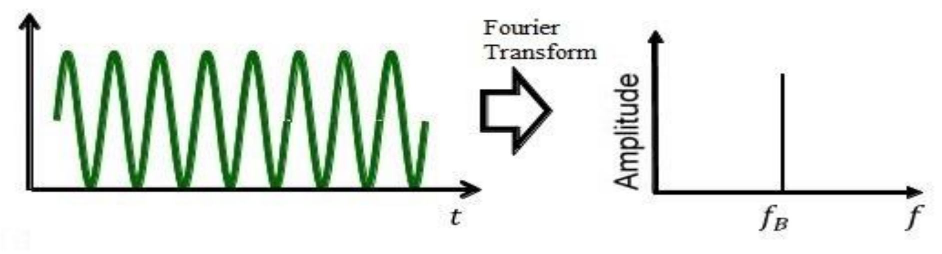

Figure 2-14: Constant beat frequency produce sharp spectrum

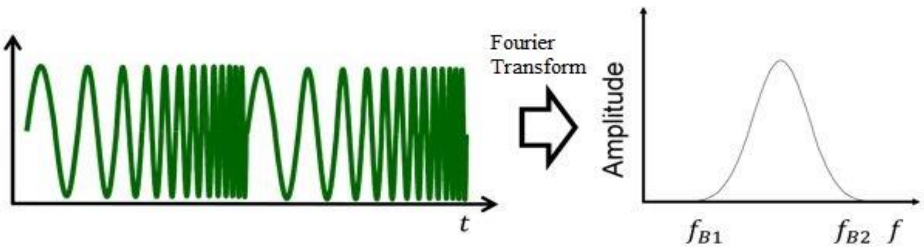

Figure 2-15: Inconstant beat frequency produce broad spectrum

To conclude, the performance of FMCW sensing interferometry is degraded by the broad spectrum shape of beat frequency which is caused by fluctuation of the beat frequency. The fluctuation (inconstant) beat frequency is then affected by a nonlinear sweep of the modulation frequency. Linear optical frequency sweep, on the other hand is difficult to obtain. This is because the optical change of frequency against injection current is nonlinear. This caused a linear optical frequency sweep cannot be accomplished even by modulating the injection current with a linear modulation triangular signal [78].

Conversely, if the frequency is linearly swept, constant beat frequency allows the system to focus at a single frequency, and the target distance's information can be extracted accurately. Fig. 2-16 summarizes the nonlinear relationship in optical FMCW system.

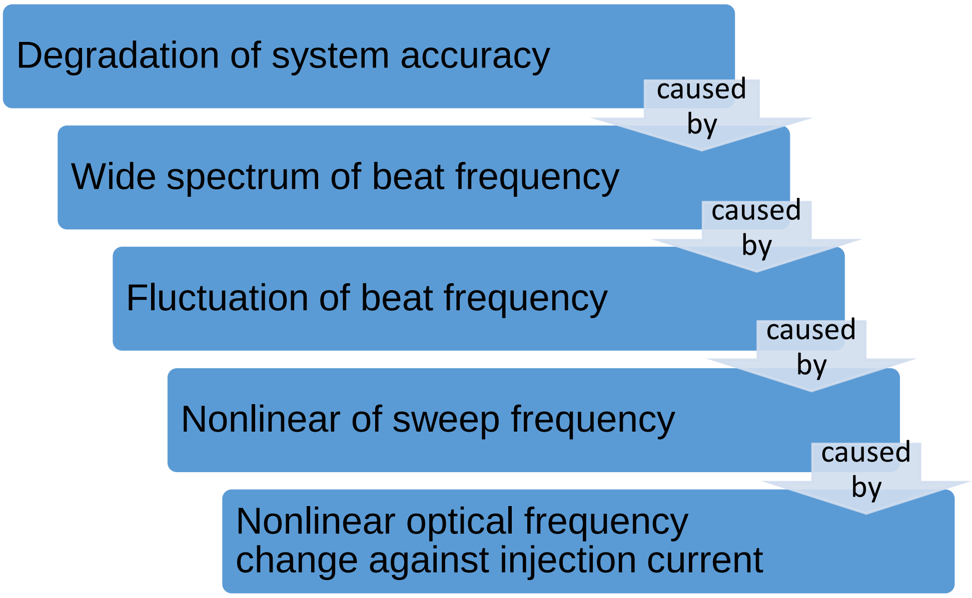

Figure 2-16: Nonlinearities relationship in optical FMCW

CHAPTER 3

CORRECTION OF NONLINEAR FREQUENCY SWEEP IN DSB LASER

3.1 INTRODUCTION

A number of optical measuring techniques that can measure both distance and velocity exist. Advance achievements in producing small tunable laser diode make this optical measurement technique becomes popular. FMCW reflectometry is assuring solution for absolute optical ranging especially in optical fiber devices and networks [78].

In basic operation of optical FMCW, the outgoing modulated light is split into a reference path and reflected path, the frequency difference between them can be calculated at the photodetector (photodiode). This frequency difference is known as beat frequency while the technique is called Frequency Modulated Continuous Wave (FMCW) [3][79].

The consistency with which the optical laser sweep frequency against injection current is not a linear function therefore, thus to achieve linearity, researchers have come out with ideas for the betterment of the system.

Many efforts have been carried out in solving this issue. For example, an external clock signal generated from an auxiliary interferometer using PLL circuit to perform synchronous sampling with the interference signal reflected from the FUT. This system is somehow limited by the measurement range in order to satisfy the sampling theorem [48] [80] [81] [82]. Another successful technique used to linearize the sweep frequency is accomplished by superimposed waveform where triangular modulation waveform is superimposed to rectangular modulation waveform. The result shows that a linear sweep of the optical frequency of the laser diode [12]

Since the known reason for nonlinear sweep frequency as describe in the earlier chapter is owing to the nonlinearity optical frequency changes against the injection current of a laser diode, thus many efforts in stabilizing the laser diode output. However, we in this research proposed a different approach. We try to resolve the issue from another direction that is by modifying the input signal that modulated the laser injection current.

3.2 BASIC CONCEPT OF WAVEFORM MODIFYING TECHNIQUE

In this sub-chapter, the main idea is to focus on linearizing the optical frequency sweep for constant beat frequency by modifying the triangular modulation waveform. Fig. 3-1 shows the nonlinear beat frequency sweep of DFB laser diode with linear triangular waveform modulating frequency. From the above figure, a little delay in frequency sweep is obviously seen that at the beginning of each rising and falling edge especially at the turning point of each interval.

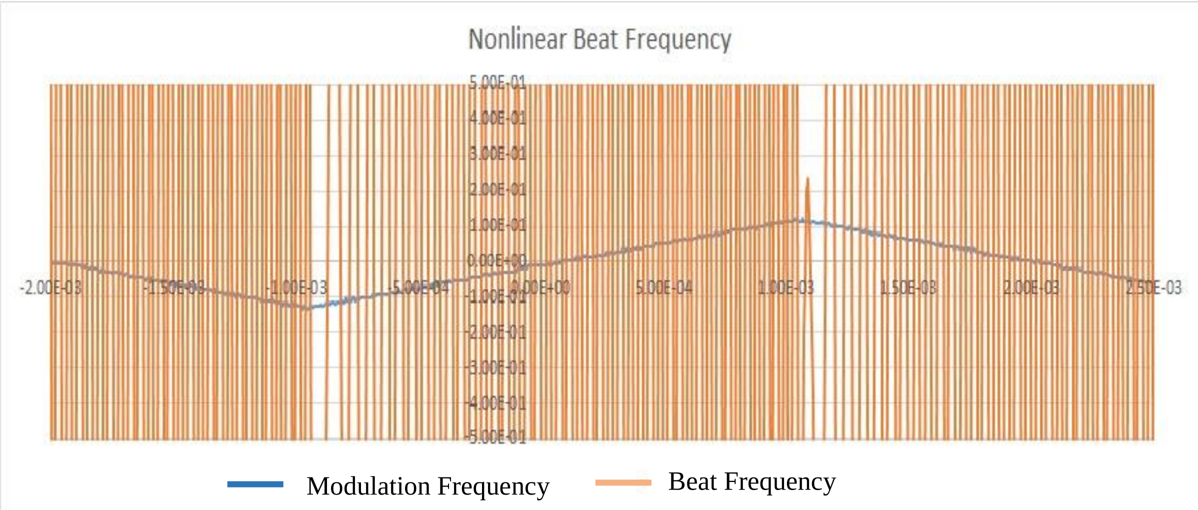

Figure 3-1: Nonlinear frequency sweep from linear modulating waveform

The nonlinear in beat frequency not only happen intra-ramp (ascending modulation interval or descending modulation interval) yet, it also occurs in inter-ramp variation due to the heating and cooling effect of a laser diode as depicted in fig 3-2.

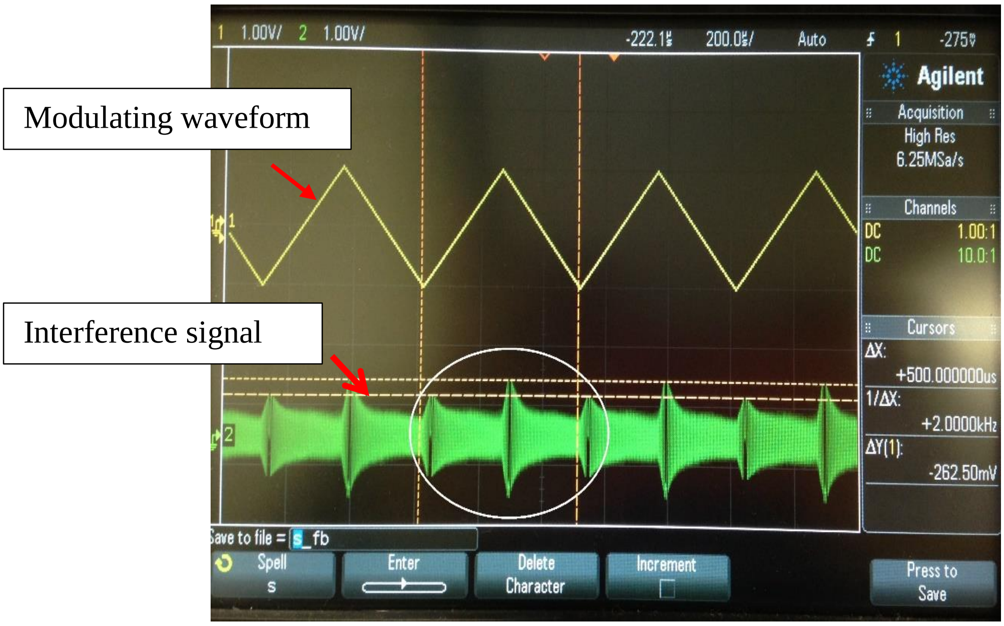

Figure 3-2: Nonlinear beat frequency variation between ascending and descending modulation interval

In order to correct or, at least improve the nonlinearity of the optical frequency sweep, the delay at the beginning of each turning point must be reduced. The interval of each cycle of interference frequency must be spaced equally. This can be done by externally sampling the reference signal with the interference signal so that all data assimilated from the interferometer have accurately identical interval.

Sweep frequency is driven by the laser diode injection current to modulation waveform; for this case we use triangular modulating waveform. For an ideal system, theoretically, linear modulation triangular waveform produces linear frequency sweep if the optical frequency change against injection current is linear. This is explained in the illustrated fig. 3-5.

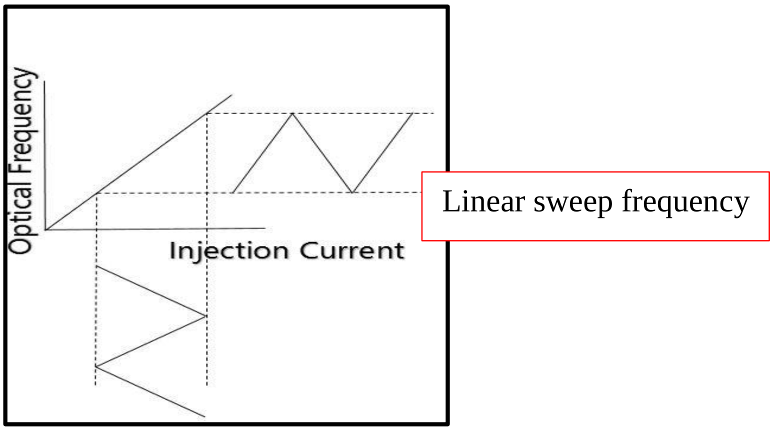

Figure 3-3: Ideal system linear optical frequency changes against injection current

Nevertheless, in fig 3-4, optical FMCW interferometry suffer from the nonlinear sweep frequency due to optical laser frequency chirp against injection current is not a linear function. Owing to this, linear modulation waveform causes nonlinear sweep frequency.

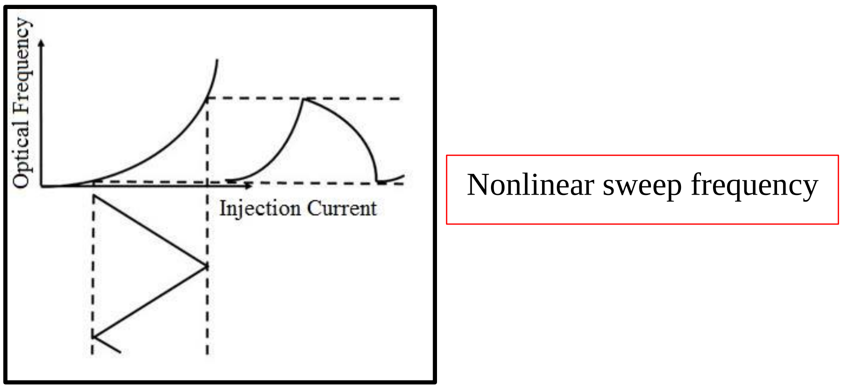

Figure 3-4: Nonlinear optical frequency change against injection current

Thus, the linearity idea is based on frequency response concept as in fig. 3-5, it is understood that linear modulation waveform of a laser frequency such as a triangular waveform results in nonlinear optical frequency change. Conversely, by modulating the injection current of a laser diode with nonlinear modulation waveform, a linear optical sweep can be achieved.

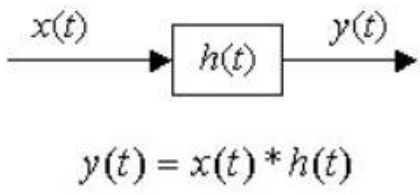

Figure 3-5: Frequency response concept

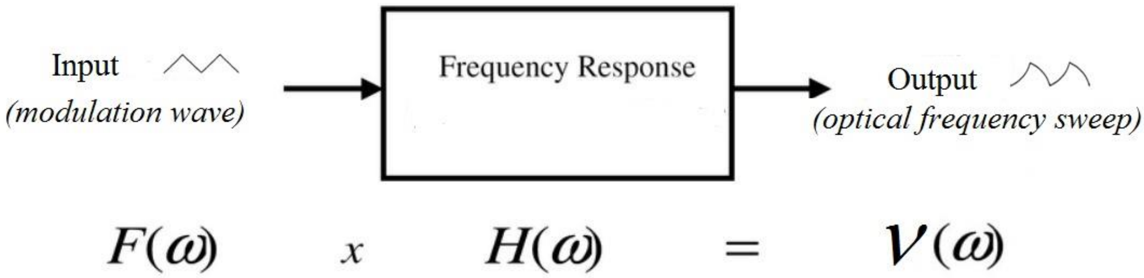

Figure 3-6: Linear input modulation waveform yields nonlinear output of sweep frequency

In fig. 3-7, the left picture shows linear modulation waveform produces nonlinear optical sweep frequency. This is based on the frequency response concept as explained earlier. Alternatively, the right picture shows that, by modulating the laser diode with nonlinear modulating triangular waveform, linear frequency sweep can be obtained.

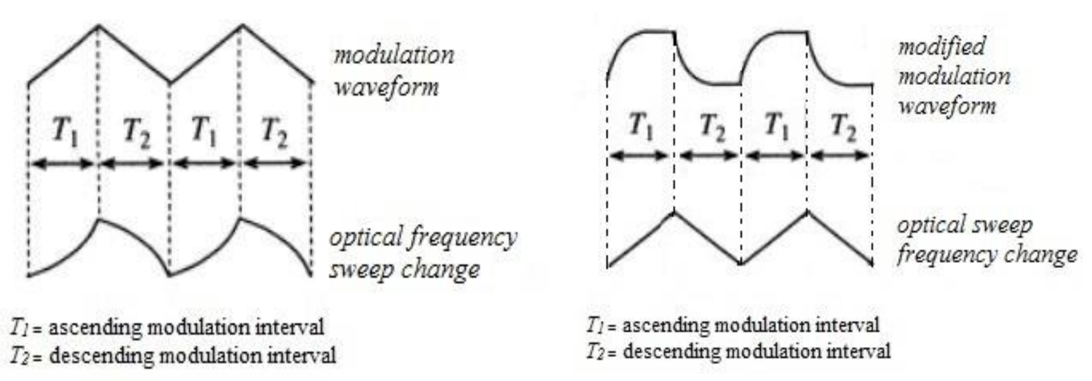

Figure 3-7: Linear and nonlinear modulation waveform effect on the sweep frequency linearity

Modulating the injection current linearly, as mentioned above, with the nonlinear relation between optical frequency changes with injection current, the sweep frequency appear nonlinear. Therefore, the feasible method is, for the optical frequency to sweep linearly, the waveform generation of the modulation current must be nonlinear.

Therefore, it is hoped that nonlinear modulation waveform will cause linear sweep. Along these lines, for the basic idea, we try to construct nonlinear modulation frequency to nonlinear injection current and perhaps linear frequency sweep can be achieved.

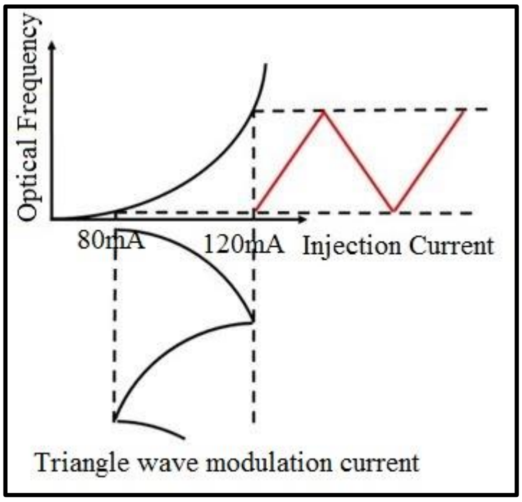

Figure 3-8: nonlinear modulation waveform produce linear sweep frequency

3.2.1 Internal and external sampling of triangular modulation waveform

Fig. 3-9 shows internal sampling performs onto triangular modulation waveform. As depicted in the above picture, the interference beat signal from the interferometer is synchronously sampled with internal sampling that generated directly from the clock generator of 12-bits AD converter device. Synchronous internal sampling did not affect the shape of the modulation waveform. Thus, the shape of the modulation waveform remains unchanged. Hence, the nonlinearity of the optical frequency sweep still exists concomitant with the unstable of instantaneous beat frequency occurs.

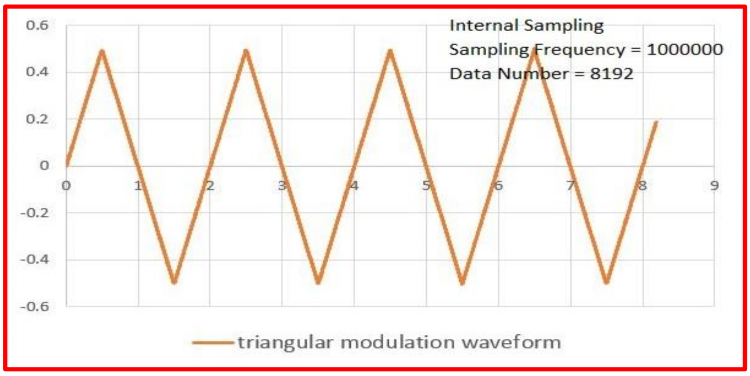

Figure 3-9: Internal sampling of triangular modulation waveform

With the idea proposed in the previous section, a synchronous external sampling of triangular modulation waveform with the interference signal from the reflected signal, are expected to cancel the nonlinearity of the optical frequency sweep of the laser source. In this case, external sampling is using its own interference signal, not from the clock generated by the generator of ADC device.

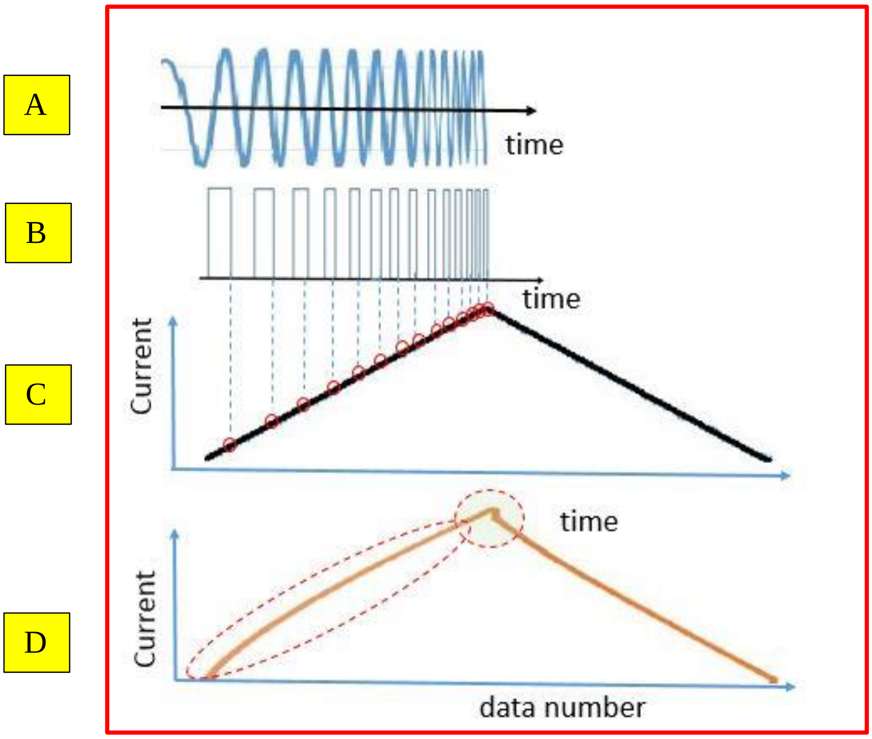

Figure 3-10: External sampling of modulation waveform

Fig. 3-10 shows how external sampling method of modulation waveform with the clock generated by interference beat signal modifies the shape of the modulation waveform.

A. The nonlinear interference signal has non-constant beat frequency

B. The nonlinear interference signal produces non-equal interval sampling clock

C. The original triangular waveform is sampled with the non-equal interval sampling clock of the interference signal of an optical interferometer.

D. External sampling to some degree change the shape of the triangle modulation waveform, the sampled waveform has tiny distortion around the turning points and slightly curved compared to the original modulating waveform.

If the optical frequency sweep is linear, the interference signal will have constant beat frequency and then the modulating waveform is sampled with equal sampling interval. As a result, the sampled waveform is the same with the modulating waveform. However, if the optical frequency is nonlinearly swept in time, the interference signal has non-constant beat frequency and then the modulating waveform is sampled with non-equal sampling interval. As a result, the sampled waveform is slightly distorted compared to the original modulating waveform. Therefore, the optical frequency sweep is linearized by modulating the laser diode with the sampled distorted waveform

External sampling clock where temporal sampling will coincide with the interference beat signal caused the shape of triangle waveform will be slightly curved and distorted. Tiny deterioration at the turning point of triangular modulation waveform was obtained as represented in figure 3-10.

CHAPTER 4

EXPERIMENT I: MODIFICATION OF MODULATION WAVEFORM

The main target of the studies in this chapter is to address the nonlinearity issue of sweep frequency by modifying the shape of the triangular modulating waveform. As discussed in the previous chapter, a slight delay in sweeping frequency occurs at each of the turning points as presented in fig. 3-1. A little acceleration on modulation waveform at that point may be essential to correct the linearity

4.1 CONSTRUCTION OF NONLINEAR MODULATING TRIANGLE WAVEFORM THROUGH EXPERIMENT

One of the successful methods to modify the shape of the modulation waveform is through frequency sampling method. By implementing an auxiliary interferometer, the triangle modulation waveform is externally sampled with the clock pulses that are generated by the interference beat signal itself. When these two signals (original triangle modulation waveform and interference beat signal) coincide, the shape of the triangle waveform is seen slightly modified. This method will be explained further in sub-chapter.

4.1.1 Experiment setup and configuration

Fig. 4-1 shows the configuration setup of FMCW interferometry technique in constructing a modified waveform of a triangular modulation signal. A triangular modulation frequency chirping is launched by the laser diode. A time difference between transmitted wave signal and reference wave signal and a delay interference signal produce a difference in frequency that is known as beat frequency. From the eq. (2-5), the beat frequency is seen proportional to the rate of frequency sweep [83].

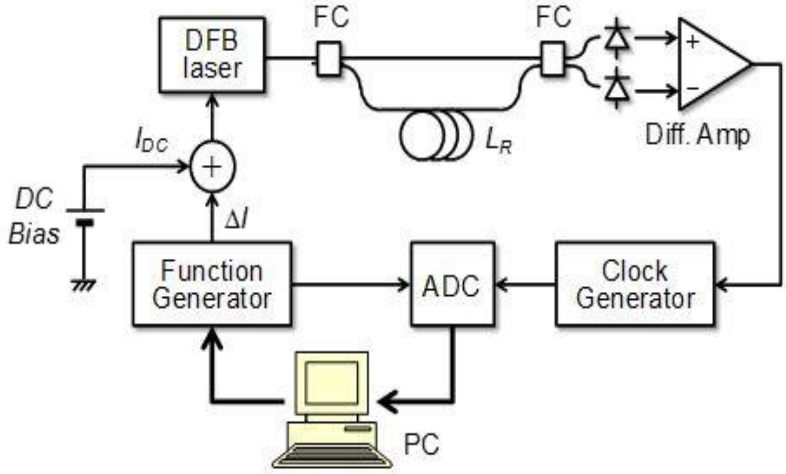

Figure 4-1: Optical FMCW interferometry setup

Parameter	Value
Waveform modulation type	Triangle
Repetition frequency	500Hz
Modulation amplitude	500mVpp
External sampling data number	8192
Delay length (P_2-P_1)	1 meter

Figure 4-2: Experiment parameters

Fig 4-2 is the parameters used with carrying out the experiment. Triangular modulation waveform fashion is used with 500Hz repetition frequency and 500mVp-p modulation amplitude. Both values of repetition frequency and modulation amplitude are randomly chosen. The data number used in this experiment is 8192 and the delay created by P_2 is 1 meter.

In order to improve the linearity and overcome the disadvantages of FMCW system, the setup testbed is configured as in fig 4-1. The proposed system was developed resembled Michelson technique with different delay created at P_2 is 1 meter. In this experiment, a DFB-LD emits 1310nm light source sweep frequency in a triangular waveform fashion. The beat interference signal of the interferometer was first passed through the LPF for choosing special frequency components, and then the signal is amplified by an amplifier, and finally converted to the sampling clock signal for external frequency sampling. As presented in eq. (2-5), the beat frequency signal is proportional to the time delay (τ) between the reference and reflected light. The reference interferometer delay time (τ) is given in eq. (2-8), with $c = 3X10^8$ m/s is the light velocity in vacuum, and $n = 1.46$ is the refractive index of fiber [78].

The triangle modulation signal is then externally sample with the non-equal interval clock pulses generated from the nonlinear interference beat signal and is then analyzed using Fast Fourier Transform (FFT).

4.1.2 Experiment chronology

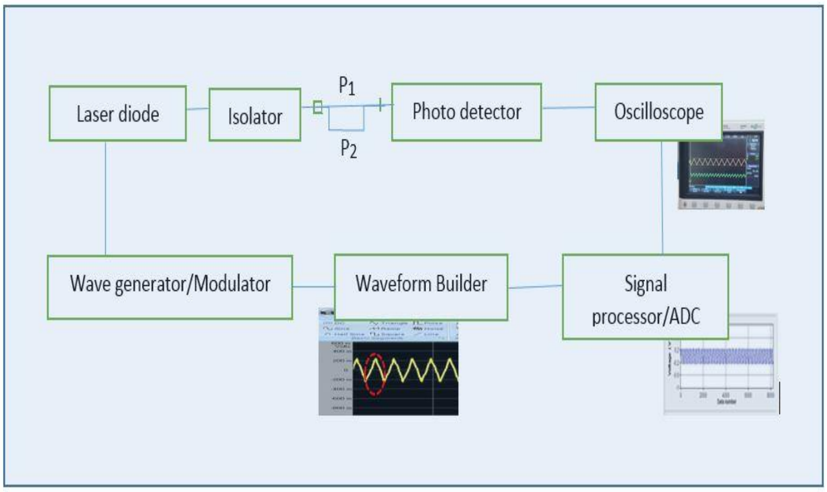

Figure 4-3: Block diagram of external sampling process

In this experiment, a triangular modulation waveform signal was sampled with non-equal sampling clock corresponding to the inconstant interval period of the interference beat signal. The sampling interval is equaled (constant) when the optical frequency is linearly swept. Contrary, the sampling interval and is varied in time if the optical sweep frequency is nonlinear. Fig. 4-3 summarize the experiment method. In the end, a modified triangular modulation waveform is obtained with tiny distortion at each of the turning points and slightly curved compare to the original modulation waveform.

The table below, encapsulates the step-by-step procedure in executing the experiment.

EXPERIMENT CHRONOLOGY

Steps	Operating Method
Step 1	Generate triangle fm wave, 500Hz at 500mVpp, and launch the laser diode to transmit the signal through P_1 and P_2
Step 2	Observe the fm triangle waveform and capture the beat frequency waveform at oscilloscope
Step 3	Signal Processor/ADC - Perform FFT analysis (external sampling at 8192 data number) and save the new fm waveform after sampling
Step 4	Import the saved waveform and using waveform builder software to extract only 1 period interval of the triangle waveform and reconstruct new fm signal waveform
Step 5	Export the new constructed fm waveform to wave generator/modulator
Step 6	Re-transmit the signal and capture the frequency beat waveform at the oscilloscope. Save the waveform.
Step 7	Perform 2nd time of FFT analysis (external re-sampling at 8192 data number) and save waveform
Step 8	Repeat step 4, 5, 6 and 7.

Table 2: Experiment chronology

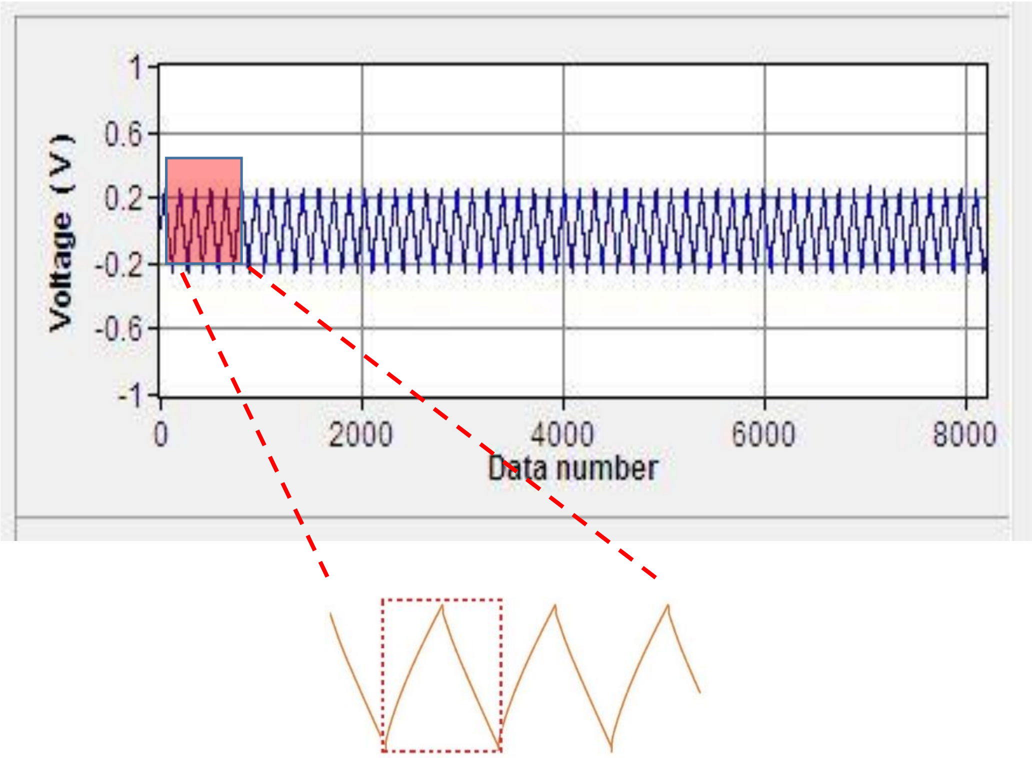

Figure 4-4: One period interval of the modulation waveform is extracted after the sampling process

After the sampling process had occurred, one-period interval of the modified sampled FM triangular signal was extracted (fig.4-4) and was used to reconstruct a new FM triangle signal using the software called waveform builder as in fig. 4-5. At this point after sampling process occurs for the first time, the shape of the modulation waveform is seen to have tiny distortion at each of the turning points and is slightly curved compare to the original modulating waveform. Then using the waveform generator, the new constructed FM triangular signal (with slight modification) was re-launched to the system. The processes were repeated until the beat frequency approached linearity.

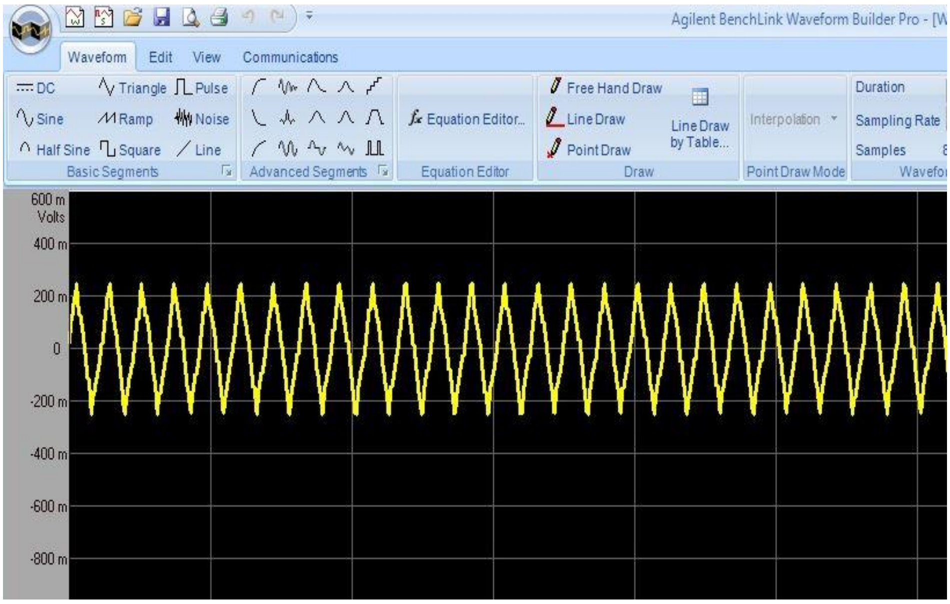

Figure 4-5: Construction of new modulating waveform from the extracted sample

In this experiment, after second iterations of external sampling, the shape of the FM triangular signal showed tiny-distortion at both high peak and the low peak of the wave. Nonlinearity at the beginning of each ramp can be slowly corrected by this resampling technique. This is because resampling the FM triangular signal creates a tiny distortion on the waveform signal, especially at the beginning of each ramp (ascending and descending modulation interval).

4.2 LINEARITY INDICATOR IN VALIDATING SWEEP FREQUENCY LINEARITY

In this subchapter, in order to estimate the linearity of the beat frequency, we will introduce a standard to benchmark the effectiveness of the proposed linearization method called *linearity indicator*. As illustrated in fig. 4-6, we will calculate the value of Δf_b using eq. (4.1)

$$\Delta fb = max\ value - min\ value \qquad \text{Eq. 4-1}$$

After that, we estimated the value of linearity indicator by using eq. 4-2.

$$linearity\ indicator = \frac{\Delta fb}{max\ value} \qquad \text{Eq. 4-2}$$

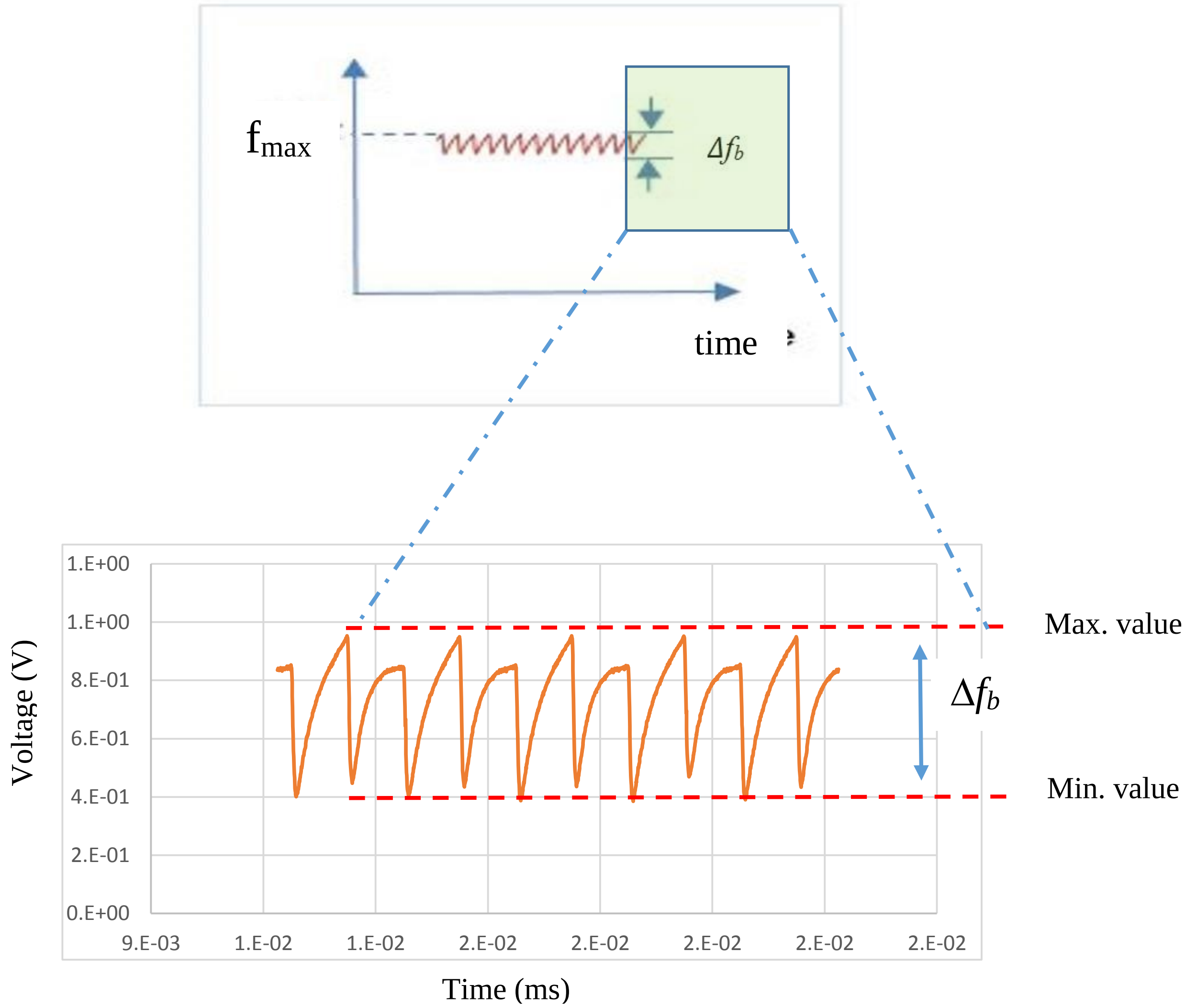

Figure 4-6: Linearity indicator of beat frequency

From the view of linearity indicator, the smaller delta frequency, the better because it shows beat frequency approaches linearity.

4.3 EXPERIMENT RESULTS

From series of experiments performed using the configuration and parameters mentioned in the previous chapter, we report the outcomes of the research. The procedure of modifying modulation waveform was done step by step and the linearity indicator was calculated to validate the effectiveness of the proposed technique.

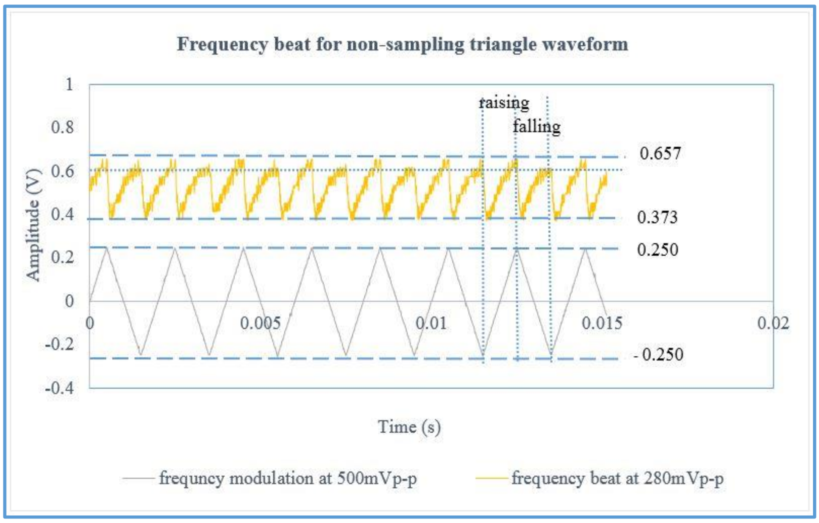

Figure 4-7: Beat frequency and modulation waveform at no sampling

Fig. 4-7 shows the shape of the bat frequency and triangle modulation waveform without undergoing the external sampling procedure. It is obviously seen that beat frequency is far from linearity. In this case, the shape of triangle modulation waveform is unchanged (similar to the original shape). Linear indicator of the beat frequency gives higher value, 0.427 as calculated below;

$$Linearity\ indicator, 0.427 = \frac{280mVpp}{655mVpp}$$

The linearity of a beat frequency can also be estimated through a beat spectrum. Interference beat signal shown in the fig. 4-7 is in the time domain. FFT analysis onto interference signal will give the spectrum view in the frequency domain. Fast Fourier transform (FFT) provides us with an alternative representation for discrete time (DT) sequences. Fig. 4-8 presented the result of the beat spectrum after FFT analysis without modulation waveform modifying the process. It shows that nonlinearity in beat frequency caused smeared and widely spread out spectrum.

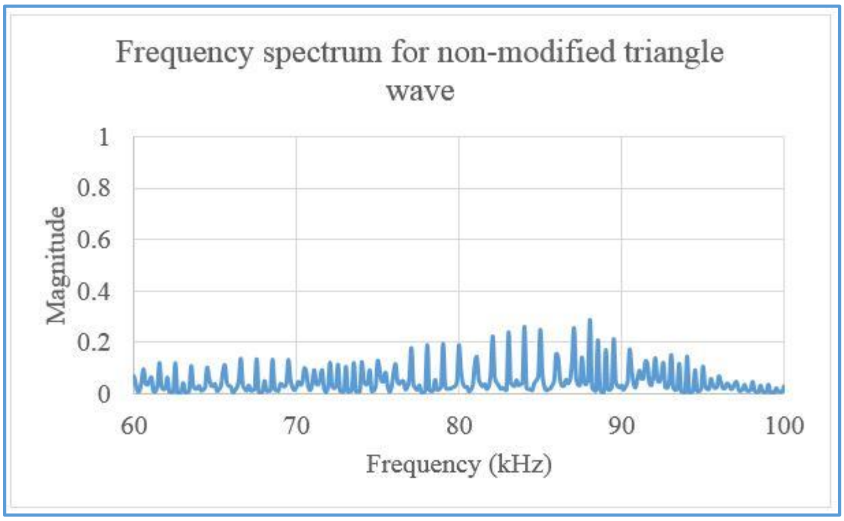

Figure 4-8: Beat frequency spectrum at no sampling

After went through the external sampling process for the first time, the shape of the triangle modulating waveform is deformed where the rising and falling edge appear slightly curve and the obvious changes are observed at each of the turning points where tiny distortion is developed. This can be seen in fig. 4-9. At this time, the difference between max value and min value decrease, Δfb become smaller and linearity indicator reduces tremendously to 0.287.

In the view of a beat spectrum, the beat frequency spectrum in fig. 4-10 shows some improvement as the bell shape can be observed.

$$Linearity\ indicator, 0.287 = \frac{163mVpp}{568mVpp}$$

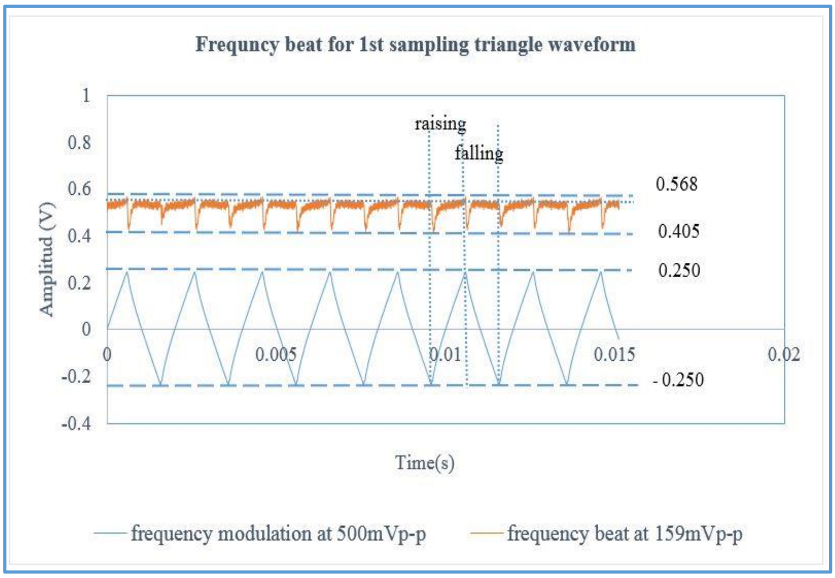

Figure 4-9: Beat frequency and modulation waveform at 1st sampling

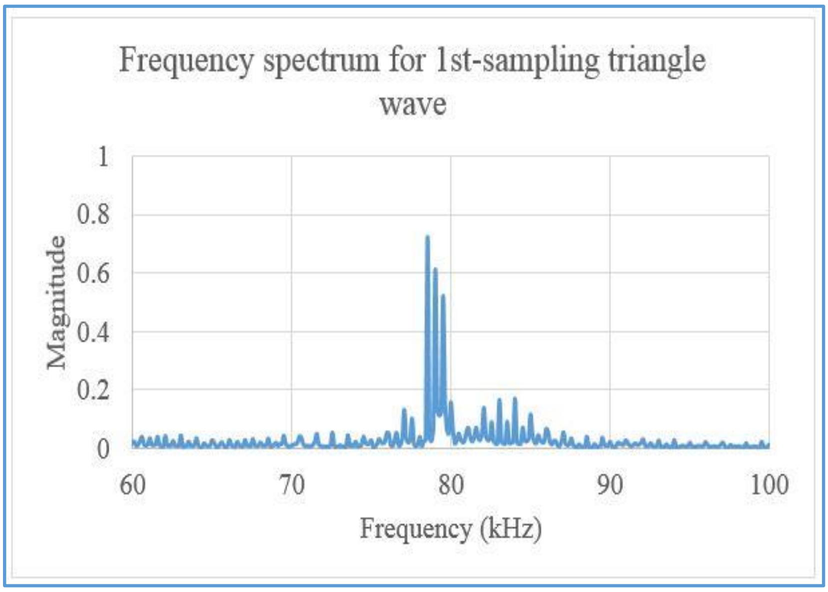

Figure 4-10: Beat frequency spectrum at 1st sampling

After repeating the procedure described above three times, an external sampling of the modulation waveform excellently modifies the shape of the triangular modulation waveform. The rising and falling edge of the modified modulation current waveform is marginally curved and small distortion after turning points is also formed.

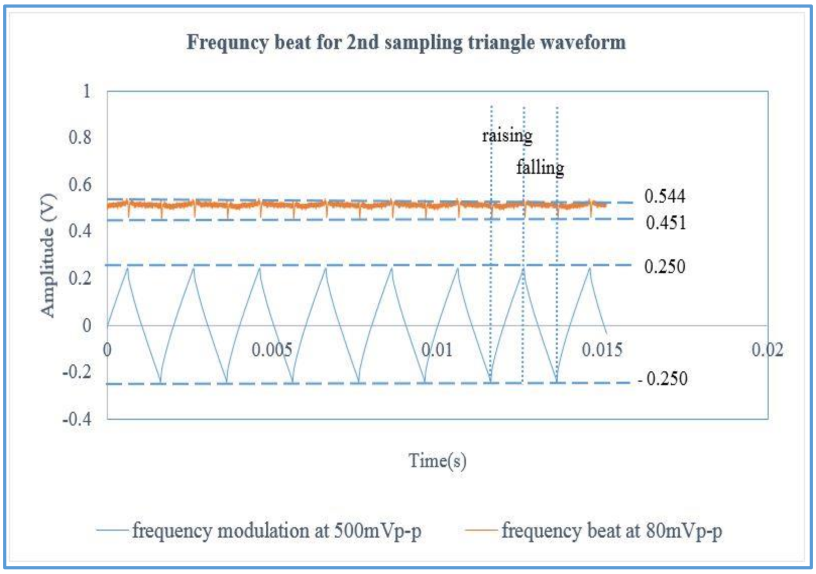

Figure 4-11: Beat frequency and modulation waveform at 2nd sampling

$$Linearity\ indicator, 0.170 = \frac{93mVpp}{544mVpp}$$

Calculation of linearity indicator is reduced impressively to 0.17. This tells us that the beat frequency spectrum approached linearity. This can be seen in fig 4-11. The fluctuation of beat frequency is almost constant except for around turning points of the modulating waveform. As a result, high spatial resolution optical ranging is obtained as represented in fig. 4-12.

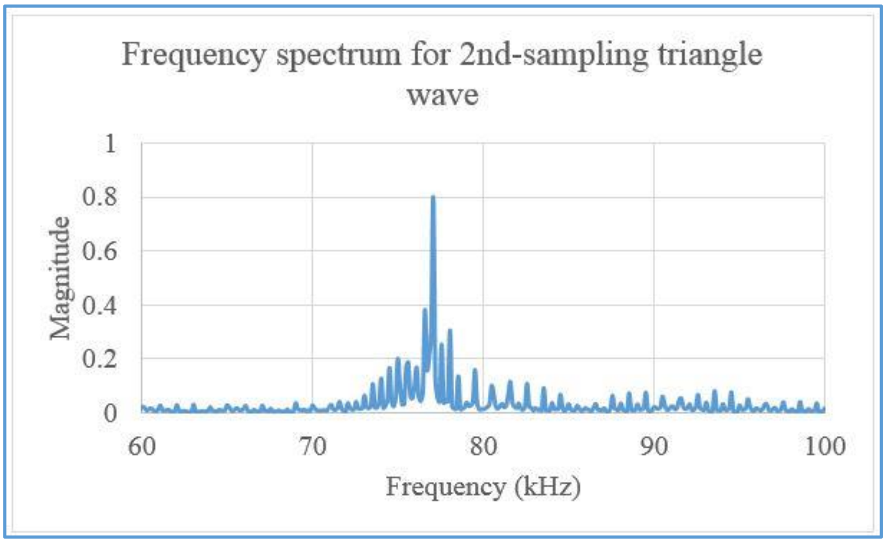

Figure 4-12: Beat frequency spectrum at 2nd sampling

Computing the value of linearity indicator $\Delta f_b/max$ every time the signal went through the sampling processes, gives us an overview of how the number of resampling times affects the beat frequency linearity. As depicted in fig. 4-13, the value of linearity indicator reduces as the number of sampling time increases. This signifies the nonlinearity of beat frequency is being rectified impressively.

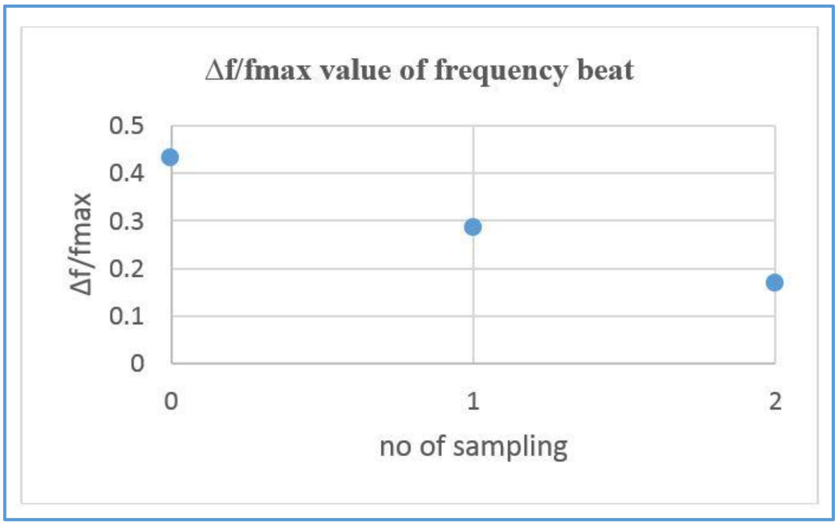

Figure 4-13: Linearity indicator of beat frequency vs no. of sampling times

4.3.1 Modulation amplitude effect on the nonlinear beat frequency

While conducting dozens of experiments, at a certain value of different parameters were chosen, the adverse effect of nonlinear beat frequency is becoming worst. It should be noted that the beat frequency change shows different traces for the increasing and decreasing section of the modulation waveform. As discussed in chapter 3, heating and cooling effect of the laser diode caused inter-ramp nonlinearity beat frequency during the in rising and falling edge of the modulation signal.

Small modulation amplitude, the difference of beat frequency nonlinearity between raising and falling isn’t obvious as in fig 4-14. However, larger modulation amplitude will cause a severe difference between the rising and falling edge because the heating and cooling temperature are slightly higher (fig. 4-15 and fig. 4-16).

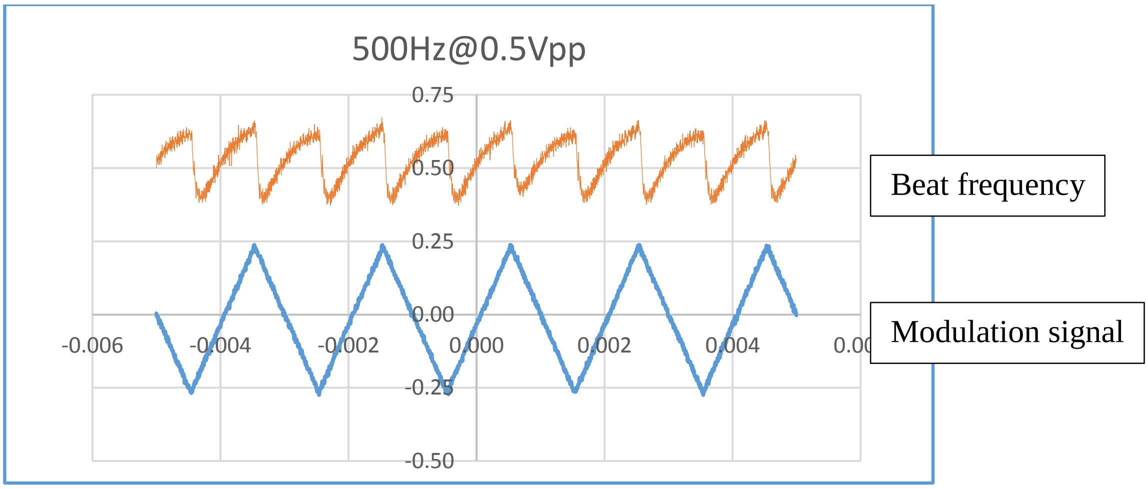

Figure 4-14: graph of beat frequency and modulation signal at 500Hz, 0.5Vp-p

In these experimental activities, the value of modulation amplitude is randomly chosen. Starting from 0.5Vp-p, we increase the modulation amplitude to 1Vp-p and 2Vp-p accordingly while the value of repetition frequency remains unchanged.

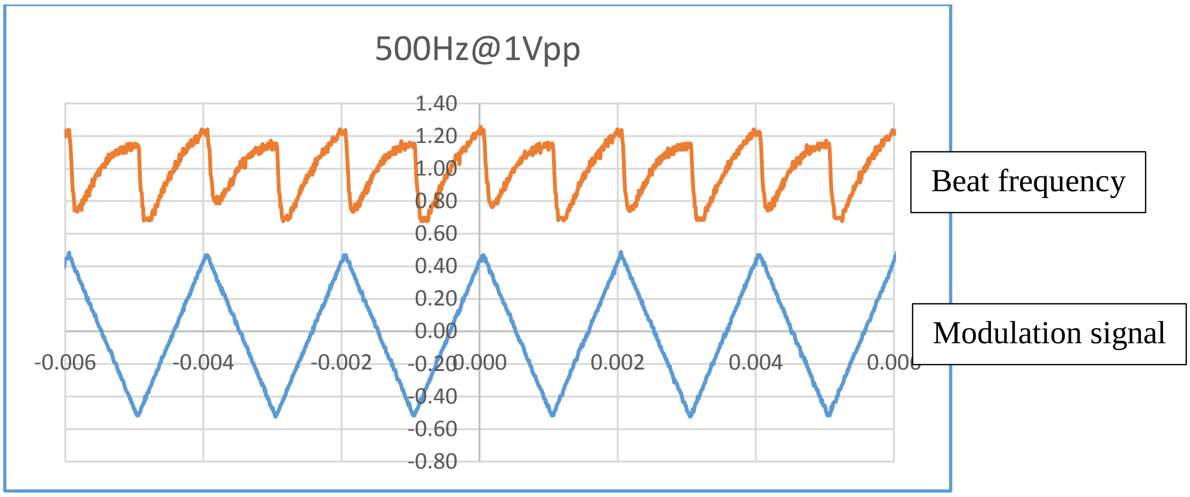

Figure 4-15: graph of beat frequency and modulation signal at 500Hz, 1Vp-p

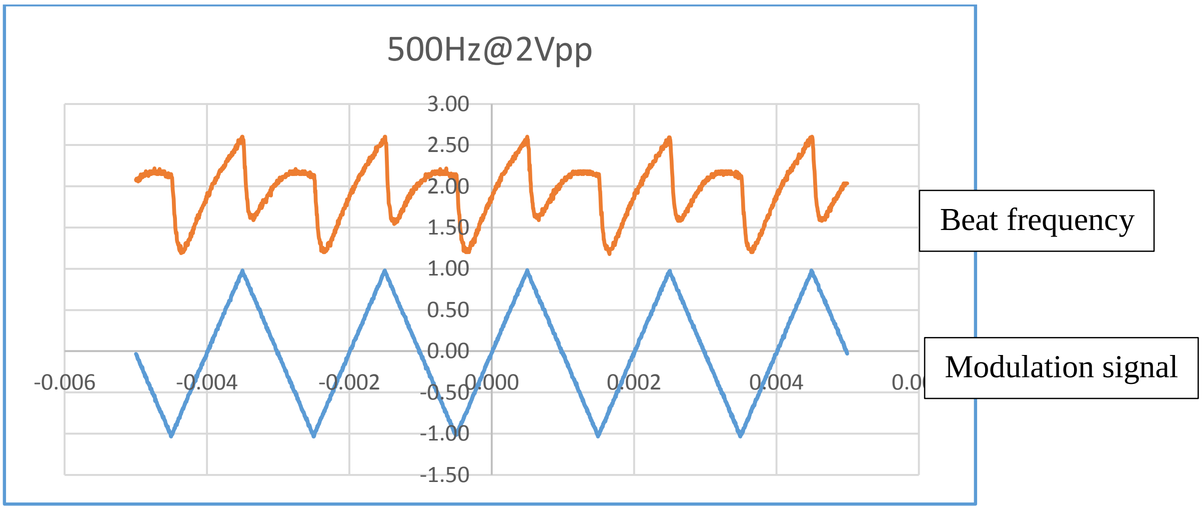

Figure 4-16: graph of beat frequency and modulation signal at 500Hz, 2Vp-p

If larger modulation amplitude applied in the experiments, it will cause severe nonlinearity in beat frequency. The difference in beat frequency change for both rising and falling interval of the modulation signal make it difficult to be rectified because the optical frequency change cannot be described by only one equation. Thus, analog or digital filter cannot be applied to compensate to solve this problem.

4.4 SUMMARY

Fig. 4-17 shows, no modification techniques applied onto modulation waveform signal. The shape of the triangle modulation wave remains unchanged and the beat frequency is considered nonlinear.

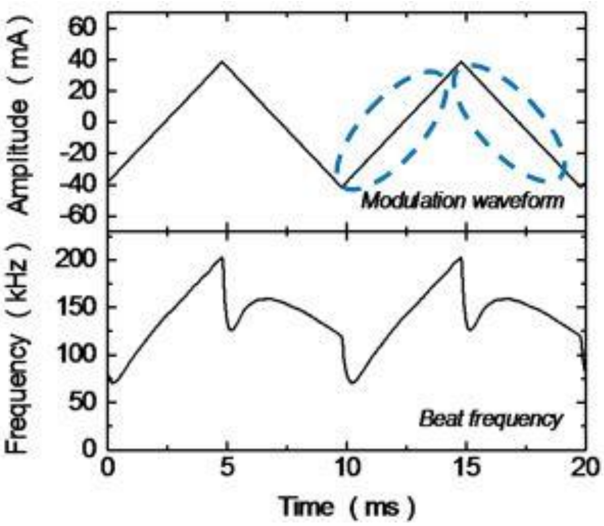

Figure 4-17: Beat frequency from modulation waveform without modification

With waveform modification technique, after being resampled with non-equal interval external sampling clock generated by the interference beat signal, the beat frequency approach linearity. The reduction on nonlinear frequency beat obtained was related to the significant change in the shape of frequency modulation signal after being sampled for 1st and 2nd time. The edge of the triangle modulation waveform slightly curved and slowly formed a tiny deterioration especially at the beginning of each rising and falling turning points of modulation as the number of sampling times increased.

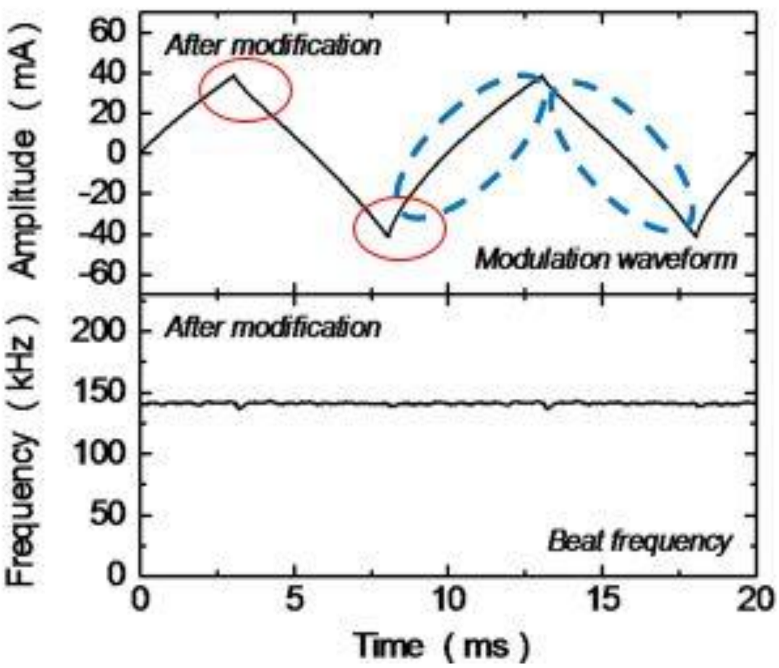

Figure 4-18: Beat frequency from modulation waveform after modification

The effectiveness of the proposed technique can also be represented in a spectrogram. The spectrogram is an informative tool in visualizing the time-depending frequency spectrum of a signal. From spectrogram, how spectral density of a signal varies in times is enlightened Fig. 4-19 and fig. 4-10 illustrated the result of the frequency spectrum for non-modified modulation waveform and modified waveform after 2nd time external sampling accordingly.

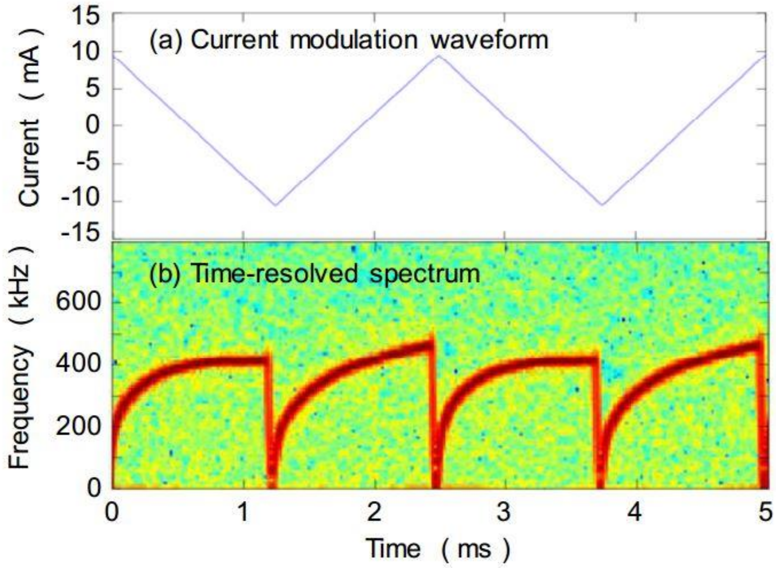

Figure 4-19: Spectrogram for non-modified modulation waveform

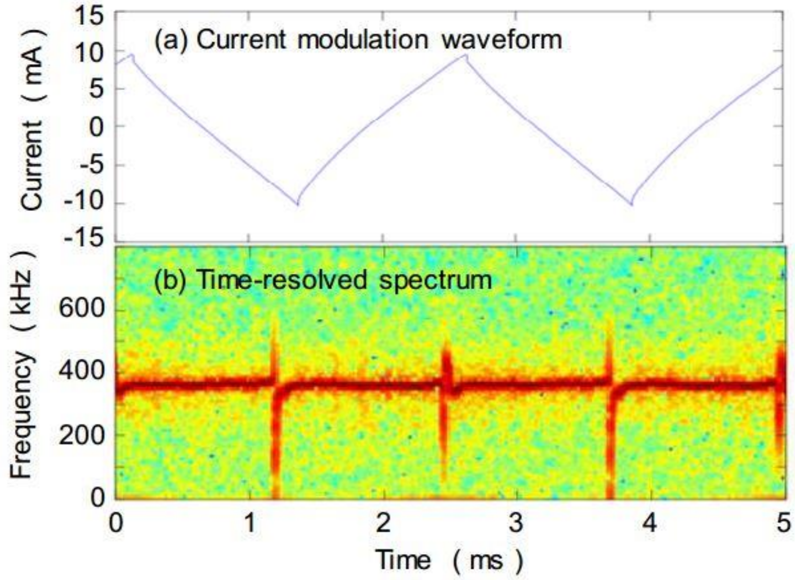

Figure 4-20: Spectrogram for modified modulation waveform after 2nd time external sampling

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To summarize, the most significant features of the proposed linearization method through modulation waveform modifying technique are:

- The instantaneous beat frequency is not constant and is gradually increased with time because of response delay of optical frequency change against the injection current of the DFB laser
- The non-sampling waveform of frequency modulation gives a larger and nonlinear value of the frequency beat.
- An external sampling of the modulation waveform excellently modifies the shape of the triangular modulation waveform. The rising and falling edge of the modified modulation current waveform is marginally curved and small distortion after turning points is also formed.
- The value of linearity indicator reduces as the number of sampling time increases.
- It should be noted that the beat frequency change shows different traces for the increasing and decreasing section of the modulation waveform
- The beat spectrum is analyzed by FFT analysis of the interference signal for decreasing section of the modulating waveform. Without modification, the beat spectrum is extremely broadened and the spatial resolution is seriously degraded. When the modulating waveform is modified (modification procedure repeated three times), a fine beat spectrum is obtained and the spatial resolution is significantly enhanced.
- The optical frequency sweep of a DFB laser is linearized and the spatial resolution of the FMCW sensing system is significantly enhanced by the proposed method

From the above results show that the proposed method for modifying modulating waveform is a very promising method to linearize optical frequency sweep and improve the spatial resolution for better reliable of FMCW sensing system.

CHAPTER 5

OPTIMIZATION OF MODULATION WAVEFORM PROPERTIES

In chapter 5, we report our research on the optimization of modulation waveform for high-resolution FMCW sensing system. While performing experiments in chapter 4, we were exposed to wide range of value in selecting the best parameters to provide optimum results. In order to ensure the most appropriate selection of parameters value, we conduct another experiment that will be explained further in this chapter. The best selections of parameters value are important in purifying the beat frequency spectrum and enhancing the spatial resolution of the FMCW sensing technique for higher system accuracy.

Regardless of other criterion, in this study, we were considering only to four parameters that we believe can contribute to the development of higher system accuracy. These parameters are repetition frequency, modulation amplitude, skip data function and zero addition in FFT analysis. Optimization of these parameters has significantly improved the spectrum resolution.

5.1 INTRODUCTION

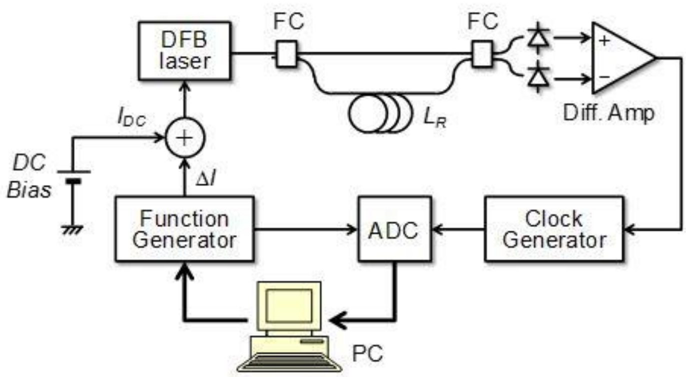

Figure 5-1: Experimental configuration

Parameter	Value
Waveform modulation type	Triangle
Repetition frequency	100-1000Hz
Modulation amplitude	10mA,20mA,40mA,60mA
External sampling at data number	2048
Delay length (L_R)	3 meter
Zero addition	0, X2

Figure 5-2: Parameters values in optimization of modulation waveform experiment

The experiment configuration for this study resembles as in fig. 5-1. The bias current of the DFB laser was 100 mA (threshold current is 10mA) and again, triangle shape of modulation waveform is launched and the signal propagated along the determined path with delay created (length) at L_R is 3 meter. The selection of parameter values is as shown in the fig. 5-2.

5.1.1 Repetition frequency

The first parameters value to be tested for its optimum result is repetition frequency. In order to elect the best value we conducted a series of experiment with a variation of repetition frequency ranging from 100Hz up to 1000Hz. The modulation amplitude, however, is fixed at 20mAp-p for all condition.

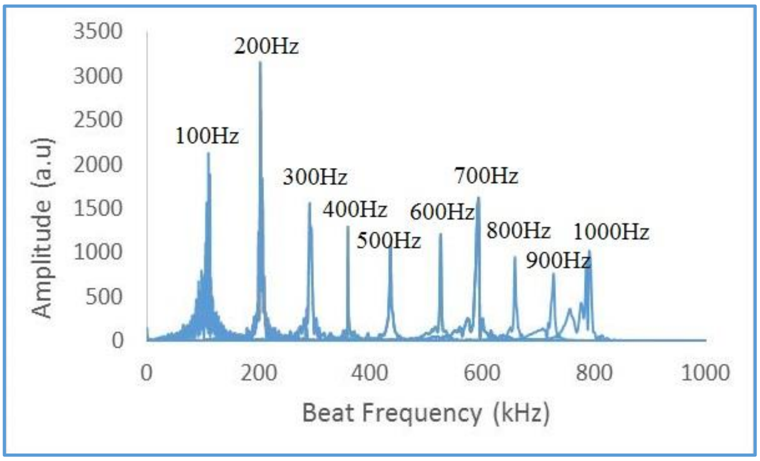

Figure 5-3: Beat frequency spectrum of repetition frequency variation from 100Hz to 1000Hz

Fig. 5-3 shows the measured beat spectrum for different repetition frequency of modulation signal after waveform modification for 3m fiber length. In overall, the beat frequency is increased as the repetition frequency and the beat spectrum is seen degraded with the increase of repetition frequency.

While repetition frequency is at 100 Hz, the beat spectrum has a pedestal, indicating the beat frequency is slightly non-constant and fluctuating in time. The reason of this issue might be due to electrical noise in the clock generator (voltage comparator) that generating a TTL signal from the interference signals for modulation waveform sampling.

From the above consideration, as represented in the fig. 5-3, the optimum repetition frequency is ranged from 200 Hz and 400 Hz, and the optimum range will be increased by carefully designing the differential amplifier and the clock generator.

5.1.2 Modulation amplitude

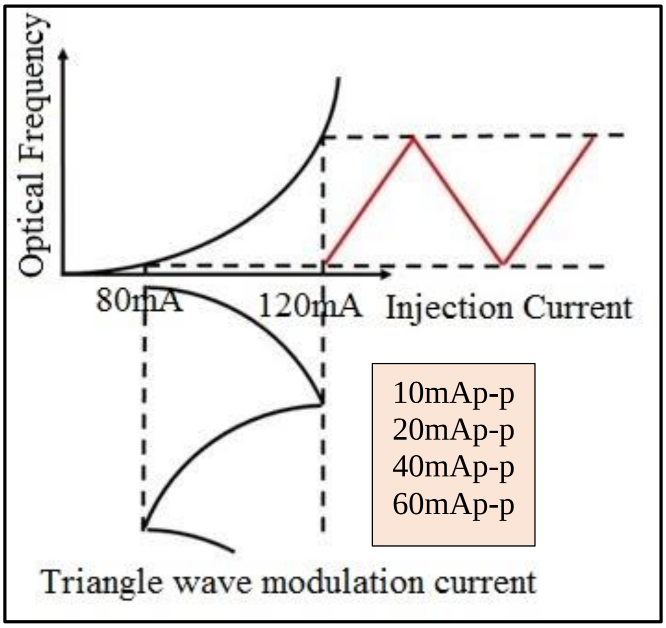

Figure 5-4: Modulation amplitude variation at 10mAp-p, 20mAp-p, 40mAp-p and 60mAp-p

The next parameter's value to be selected for optimum condition of modulation waveform is modulation amplitude. As cover in the sub-chapter 4.3.1, modulation amplitude has a big influence in the linearity of the beat frequency. The beat frequency linearity differences between rising and falling edge interval of the modulation signal is getting worse as the modulation amplitude value increase. Therefore, we performed this experiment in order to decide the best value of modulation frequency for better accuracy of the system. In this experimentation, the injection current of the modulating triangle waveform for are varied at 10mAp-p, 20mAp-p, 40mAp-p and 60mAp-p (500mVpp, 1Vpp, 2Vpp & 3Vpp respectively) at predetermined repetition, 400Hz. The 400Hz is chosen for its best result in the earlier experiment.

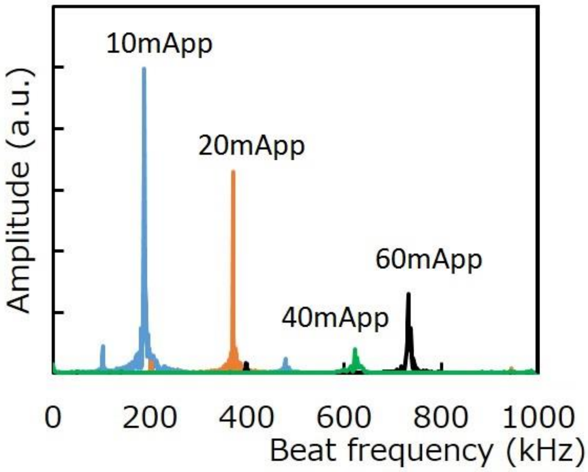

Figure 5-5: Beat frequency spectrum of modulation amplitude variation from 10mApp to 60mApp

Fig. 5-5 shows the shape of beat spectrum for variation of modulation amplitude values ranging at 10mApp, 20mApp, 40mApp and 60mApp. The relationship between optical sweep frequency and injection current can be represented by the following relationship, $\Delta I \infty\ \Delta F$. In other words, the optical sweep frequency ΔF is proportional to the injection current of the modulation signal. Consequently, from eq. 2-6 in chapter 2, the increased in sweep frequency directly will increase the beat frequency.

From fig. 5-5, the fine beat spectrum purification is seen for the modulation amplitude of 10mAp-p and 20mAp-p, and the beat spectrum is degraded with increasing the modulation amplitude. The reason of spectrum degradation is unclear but the electrical noise in the clock generator might be the reason since the decreased in the amplitude of interference signal owing to the limited bandwidth of the differential amplifier.

5.1.3 Skip function in FFT analysis

The next parameter's value to be experimented is skip function in FFT analysis. Before going into further details of skip function, an understanding of data number is essential because, in the analysis of skip function, it involve of data number usage.

Data number is the number of data sampled in the time domain (N). In Fourier transform, the efficient number of sampled data is N/2 corresponding to the maximum measurement range to satisfy the Sampling Theorem [78]. For F_s/N, where F_s is input signal sampling rate (sampling frequency) and N is a number of FFT points used, to get smaller bin FFT, we can either run the FFT longer or we can decrease the sampling rate F_s.

Skip number generally helps in performing the FFT analysis efficiently because we can eliminate or skip the unwanted signal without jeopardizing the total number of data points. This is important because it tells us that the absolute information of the interference signal is preserved.

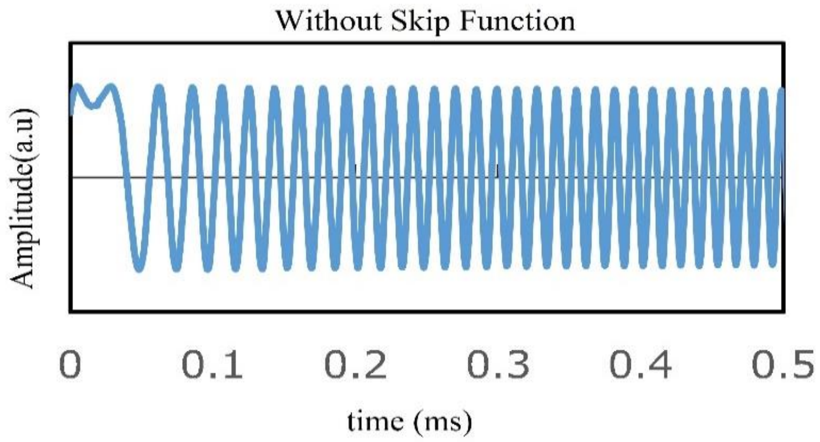

Figure 5-6: Interference signal without skip function

The optical frequency sweep of a DFB laser is linearized and the spatial resolution of the FMCW sensing system is significantly enhanced by the proposed method in the previous chapter. However as shown in Fig.5-6, perfect linearization cannot be achieved because the beat frequency just after the turning point of the modulation waveform is not constant. Therefore, a small fraction of the interference signal immediately after the turning point between ascending modulation interval and descending modulation interval of the modulation waveform was skipped for data acquisition for high-resolution distance measurements [75].

The default skips no is 0, meaning that the whole signal is captured including the unwanted signal. As illustrated in fig. 5-6, at the starting of turning points of the modulation signal, interference beat signal is in constant even after applying the modifying waveform technique. A little delay is seen before the solid steady signal succeeded.

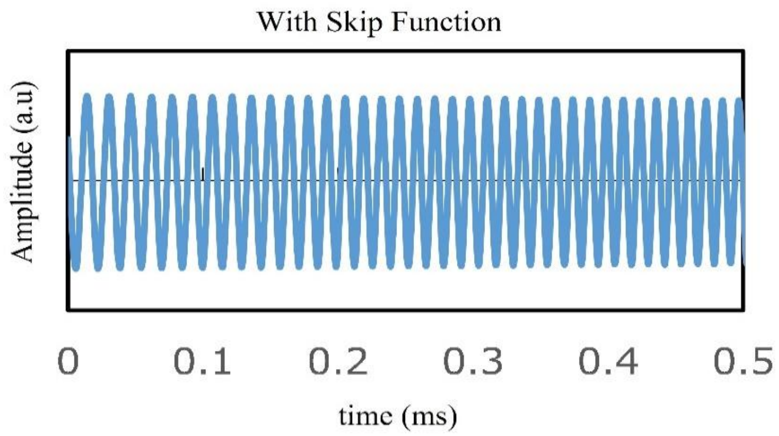

Figure 5-7: Interference signal with skip function

The experiment of this section began with omitting (skipping) data at various percentages. After series of trial, the most considered percentage of data to be skipped was achieved. The preceding parameters, repetition frequency, and modulation amplitude were maintained at 400Hz and 20mApp respectively.

5.1.4 Zero addition in FFT analysis

Zero adding or zero padding function in FFT analysis indicate the action of inserting (adding) zeros “0” to end of a time domain in order to increase its length. This is a popular technique for taking a bigger FFT to make the beat spectrum more readable.

In the effort to get longer FFT for higher resolution, we can increase the number of data to be sampled. However, if the number of the sampled data is increased, the sampled data contains the interference signal around the turning point of the modulation waveform, and as a result, the beat spectrum is degraded because of beat frequency fluctuation just after the turning point of the modulation waveform [79].

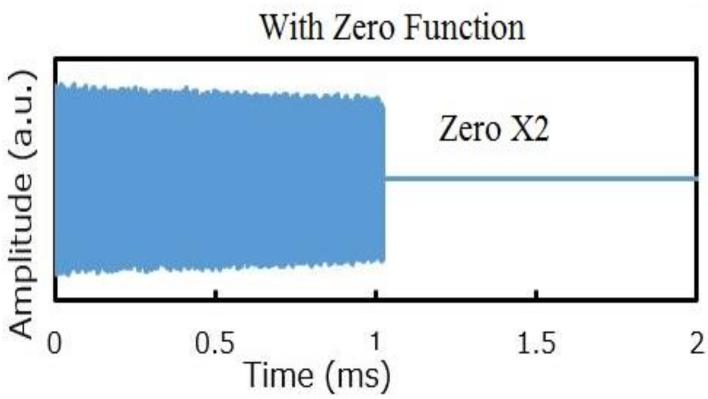

Figure 5-8: Interference signal with zero adding function

Instead of increasing the number of sampled date, after undergoing skip function, we added zero values after the sampled data. In our experiment, the number of sampled data is 2048 and more 2048 points of zero data are added. This will double up the length of total times.

5.2 FWHM

The beat frequency spectrum is very important factors in representing the accuracy of the system in overall. The non-linearity in the frequency sweep can cause a nonlinear frequency beat. FFT analysis showed that nonlinearity issues affect the broadening of the frequency spectrum of the interference beat signal.

Optical frequency sweep linearity is estimated by the spatial resolution of the beat spectrum. For narrow spectrum, accurate data can be extracted and the targeted distance precisely measured. So, how do we evaluate beat frequency purification?

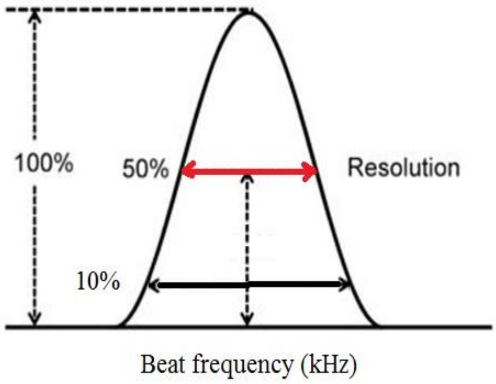

Figure 5-9: FWHM concept

$$\delta f0.5 = \frac{\text{full width at 50\% max}}{fb} x\ 100\% \qquad \textit{Eq. 5-1}$$

$$\delta f0.1 = \frac{\text{full width at 10\% max}}{fb} x\ 100\% \qquad \textit{Eq. 5-2}$$

The purification of beat spectrum is estimated by means of two kinds of the spectral width of the beat spectrum; the full width at half maximum of the beat spectrum, full width at 50% of maximum (d$f_{0.5}$) and full width at 10% maximum (d$f_{0.1}$)

The beat spectrum purity is estimated as d$f_{0.5}$ / f_b and d$f_{0.1}$ / f_b, where f_b is the frequency for peak amplitude. A small value of d$f_{0.5}$ / f_b and d$f_{0.1}$ / f_b means high spectral purity and then means high spatial resolution.

5.3 EXPERIMENT RESULT

5.3.1 Repetition frequency and modulation amplitude

At the end of the experiment, the result shows the purity of the beat spectrum against the repetition frequency of the modulation signal for different modulation amplitudes, which is evaluated by the full width at half maximum relative to the beat frequency, $df_{0.5}$ / f_b, as in fig. 5-10 and full width at 10% maximum, $df_{0.1}$ / f_b as in fig. 5-11.

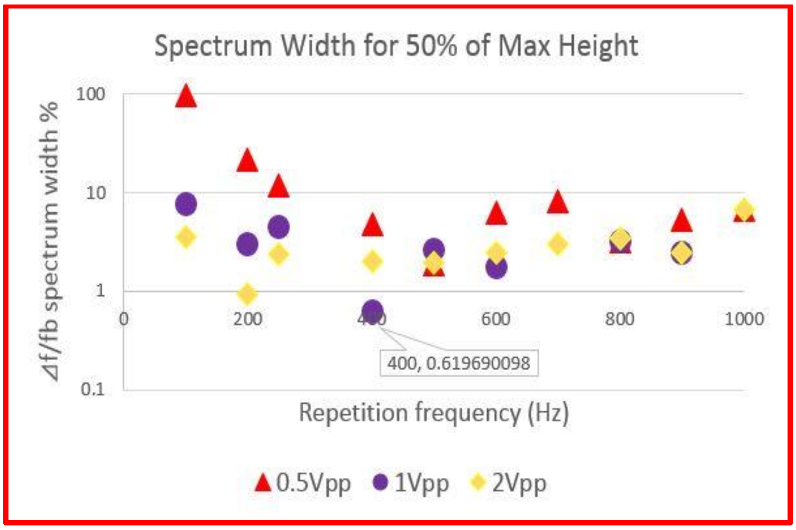

Figure 5-10: FWHM at 50% of max

From the above figure, $df_{0.5}$ calculated using eq. 5-1 gives the overall view of beat spectrum purification. The best value for repetition frequency and modulation amplitude is at 400Hz, 1Vpp respectively for 3m fiber length.

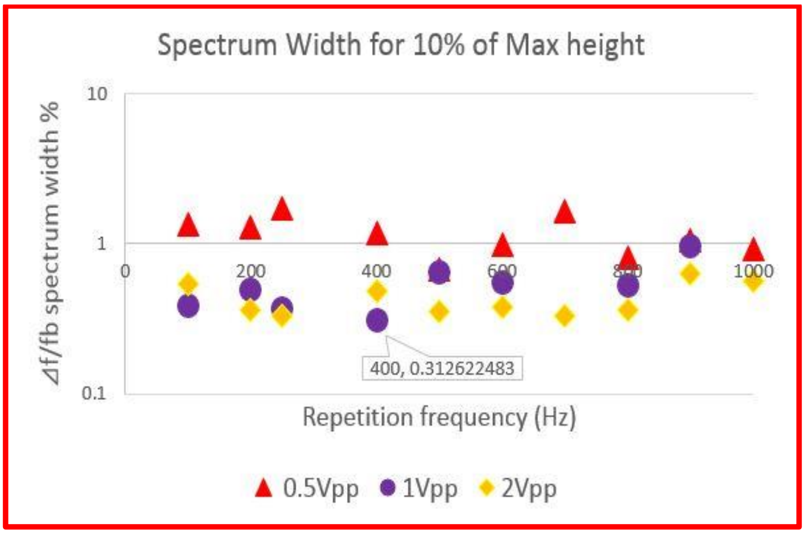

Figure 5-11: FWHM at 10% of max

For $df_{0.1}$, modulation amplitude of 1Vpp shows the lowest value at 400Hz repetition frequency. In this case, the optimum beat spectrum purification is obtained for 400Hz repetition frequency and 20mApp (1Vpp) modulation amplitude. Resolution can be estimated using eq. 5.4. Since the relative 50% width is less than 1% (from the above graph), resulting in the spatial resolution of less than 3 cm for L_R = 3m

$$\Delta Z = \frac{df}{fb} x\ LR \qquad \textit{Eq. 5-3}$$

5.3.2 Skip function in FFT analysis

The measured beat spectrum without skip function and with 15% acquisition skip just after the turning point of the modulation waveform for repetition frequency 400 Hz with 20 mA modulation amplitude are shown in fig 5-12 and fig. 5-13 respectively.

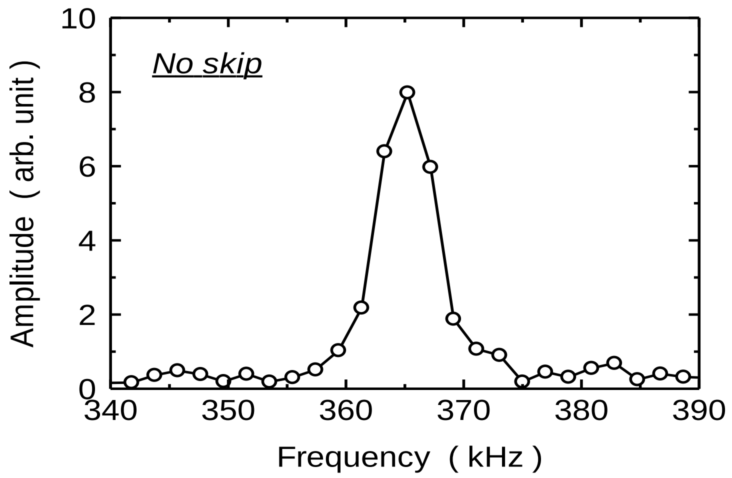

Figure 5-12: Beat frequency spectrum without skip function

Without skip function, the beat spectrum is seen broaden compared to 15% acquisition skip. Narrower beat spectrum is obtained by utilizing acquisition skip because the beat frequency fluctuation just after the turning point is eliminated.

The result in fig. 5-13 is executed with sampling frequency is 4 MHz, number of sampled data is 2048, and the acquired time is 0.512 ms, (40% of the decreasing section of the modulation waveform) in 2 kHz frequency interval. Skip function makes the beat spectrum more readable.

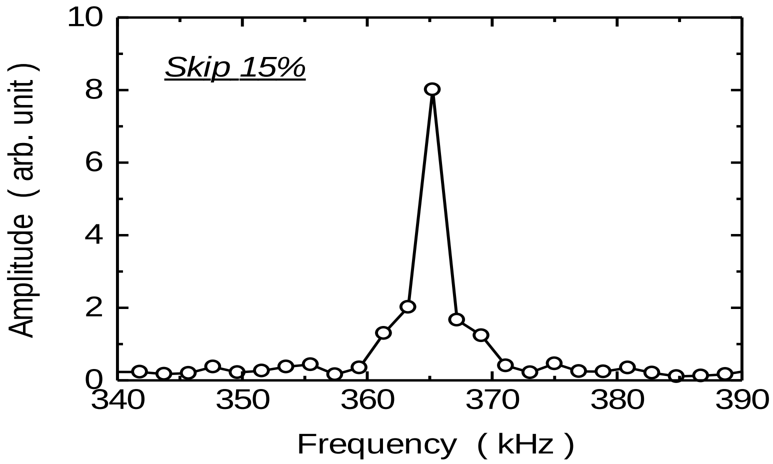

Figure 5-13: Beat frequency spectrum with skip function

5.3.3 Zero addition in FFT analysis

Zeros adding function (aka zero padding) is a commonly used technique that associated with skip function FFT analysis. By inserting “0” at the end of the sampled data, we can double up the total times and this will improve the interpolation in the transformed domain.

From eq. 5-3, since the interval gaps of data in the frequency domain, is in inverse proportion to the number of data samples in the time domain, thus, by inserting zeros, more data points in the frequency domain is obtained for identical frequency range. Hence, the added zero function holds more data point than the non-added zero. Consequently, a better times representation of FFT.

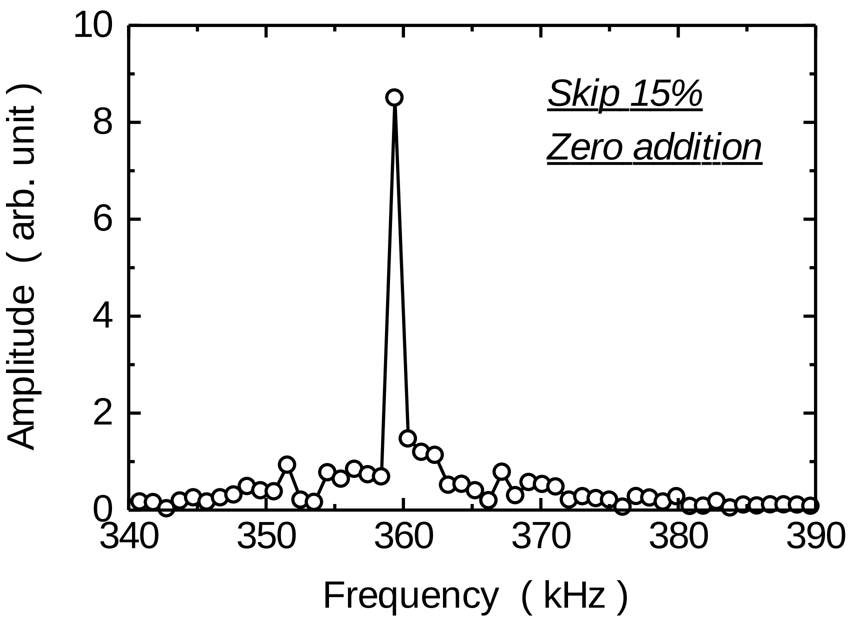

Figure 5-14: Beat frequency spectrum with 15% skips data function and zero padding X2

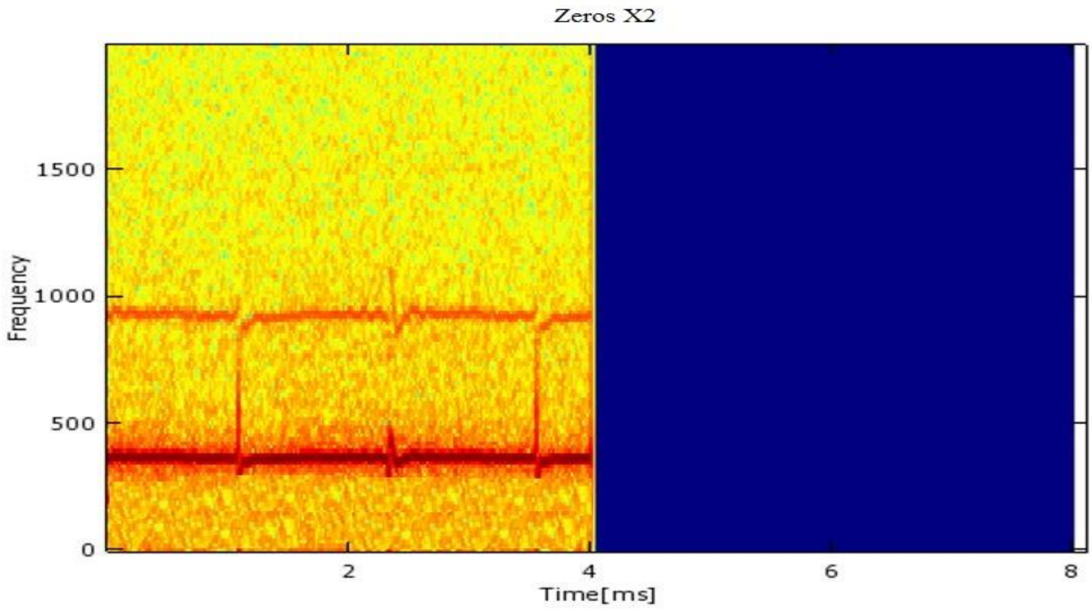

Figure 5-15: Spectrogram with 15% skips data function and zero padding X2

Fig 5-15 is the result of acquisition skip after the turning point at 15%. The frequency interval is about 1 kHz, which is half of the frequency interval before Zero Addition, the beat spectrum is narrower with 0.33% of the relative 50% width $df_{0.5}$ / f_b, resulting in the spatial resolution of 1 cm. Frequency interval is decreased, so higher resolution is achieved. Fig. 5-16 shows the beat spectrum with 15% skip data function and zero addition X2 in view of the spectrogram.

5.4 SUMMARY

To summarize, the main purpose of experiments conducted is to enable us to make the right selection of parameter's value to obtain clean and purified beat spectrum for optimum results. So for this chapter, the effectiveness of the proposed linearization method is measured by the beat spectrum purity with different repetition frequency and modulation amplitude, and FFT analysis.

Variations of repetition frequency and modulation amplitude value chosen provide a different result. The best combination of these two parameters value will give a big impact in beat spectrum purification. The interference signal just after the turning point of the modulation waveform is skipped from sampling because the optical frequency sweep immediately at that spot is not perfectly linearized and this caused the beat frequency fluctuated. And zero data are added after the sampled data to decrease frequency interval in FFT analysis while avoiding acquisition of the interference signal at the turning point between ascending modulation interval and descending modulation interval of the modulation waveform. Below are the considerations and observations in this experiment:

- Laser phase-noise induced intensity noise is also a noise source because optical frequency fluctuation (that is, frequency noise or phase noise) is converted into optical intensity fluctuation in an optical interferometer because the output power of an optical interferometer periodically changes against the optical frequency change.
- Skip data function helps to accurately measure the data in the right location of the signal. It should be noted that the total number of data points almost keep unchanged during the time examine the skip number, which means the information of the interference signal is preserved
- The frequency interval is determined by the total acquisition time (bigger data number). The frequency interval has a significant influence on the spatial resolution, and narrow frequency interval is desired for high-resolution measurement.

As a result, by repeating the waveform modification procedure a few times, the optical frequency sweep is linearized, and then the spatial resolution of FMCW sensing system is significantly improved. The degree of linearization of optical frequency sweep depends on both the repetition frequency of the modulation signal and the modulation amplitude. In our experiments, the optimum repetition frequency is about 400 Hz from the viewpoint of spatial resolution, and the optical repetition frequency range can be expanded by decreasing electrical noise in the clock generator.

CHAPTER 6

SUMMARY

Optical FMCW interference has offered a great opportunity in modern communication and has benefited all humankind. It has important advantages in contributing high resolution, larger measurement range and offer an absolutely accurate and precise measurement especially in fiber optical fields.

- Nonlinear issue in sweep frequency of DFB laser is corrected through the proposed linearization technique; modification on the triangle modulating wave
- In this research through waveform modifying technique, after repeating the process three times the optical frequency sweep is linearized, and then the spatial resolution of FMCW sensing system is significantly improved
- Beat frequency spectrum is purified by waveform optimization for high-resolution FMCW interferometry
- The degree of linearization of optical frequency sweep depends on both the repetition frequency of the modulation signal and the modulation amplitude also influence by skip function and zero adding properties during FFT analysis.
- In our experiments, the optimum repetition frequency is about 400 Hz from the viewpoint of spatial resolution, and the optical repetition frequency range can be expanded by decreasing electrical noise in the clock generator.
- Skip data function and zero data addition are added after the sampled data to decrease frequency interval in FFT analysis while avoiding acquisition of the interference signal at the turning point between ascending modulation interval and descending modulation interval of the modulation waveform.

6.1 CONSIDERATION

These are the factors that we put into our considerations towards achieving the main objective of the research studies.

- Beat spectrum behaviors that rely on the relationship between repetition frequency and modulation amplitude, rising and falling edge, fiber length, FFT properties such as skip data function and zero padding function.
- Capability of FFT analysis that limited by the memory and ram of PC and other devices
- Experiment configuration based on Michelson technique only
- Modulation waveform was performed for triangular shape only

6.2 CONTRIBUTION

In overall, the research studies in optical frequency sweep linearization of a DFB laser for high-resolution FMCW reflectometry has brought many major issues into contributions

- Locate the root cause of the fundamental problem of nonlinear sweep frequency that is the effect of the injection current on the beat frequency.
- Rectify the nonlinear issue of beat frequency by correcting the sweep frequency linearity through waveform modulation modifying technique.
- Come out with the linearity indicator to support the debate in validating the beat frequency linearity.
- Best combination selection of repetition frequency and modulation amplitude, FFT properties such as skip data function and zero padding for beat spectrum purification and frequency interval
- Evaluation of beat spectrum purification through FWHM

6.3 CONCLUSION

In conclusion, the effect of nonlinear optical frequency sweep is canceled from modification of modulation waveform through the sampled beat signal of the beat interference. Proper selection certain parameters value can sharpen the beat spectrum and improve the resolution (frequency interval) of the spectrum. As a result, the beat frequency approached linearity, the degradation of the spatial resolution is considerably improved as well as the measurement accuracy greatly increased.

1) Based on first experiment analysis, linearity indicator Δf_b/max, the beat frequency linearity is improved from 0.427 to 0.170, approximately 60% reduction in nonlinearity.
2) From the second experiment, based on FWHM estimation, frequency interval of the beat spectrum was reduced from 3cm to 1 cm (based on 3-meter fiber length) estimated to 66% resolution intensity improved.

Thus, we conclude the objective of this research “Optical frequency sweep linearization of a DFB laser for high-resolution FMCW reflectometry” is achieved.

REFERRENCE

[1] W. E. N. Chuanhua and L. I. Yuquan, “Research on smart antenna for inter-satellites laser communication,” *IET Int. Conf. Wirel. Mob. Multimed. Networks Proc. (ICWMMN 2006)*, vol. 2006, pp. 126–126, 2006.

[2] K. G. Johannsen, “Measurement of Satellite Communication Parameters : Satellite Antenna Measurements,” *Instrumentation*, vol. 37, no. 2, pp. 285–291, 1988.

[3] D. Nordin and K. Hyyppä, “Using a discrete thermal model to obtain a linear frequency ramping in a frequency-modulated continuous-wave system,” *Opt. Eng.*, vol. 44, no. July, p. 074202, 2005.

[4] G. Berkovic and E. Shafir, “Optical methods for distance and displacement measurements,” *Adv. Opt. Photonics*, vol. 4, no. 4, p. 441, 2012.

[5] A. Lazam, K. Iiyama, T. Maruyama, Y. Kimura, and N. Van T, “Linearization Of Nonlinear Beat Frequency In FMCW Interferometry Through Waveform Modifying Technique,” *ARPN J. Eng. Appl. Scinces*, vol. 10, no. 8, pp. 3817–3822, 2015.

[6] “Extended-Range Optical Low-Coherence relfectometry using a recirculating delay technique.” .

[7] E. Brinkmeyer and U. Glombitza, “High-resolution coherent frequency-domain reflectrometry using continuously tuned laser diodes,” in *Tech. Dig. Conference on Optical Fiber Communication*, 1991, p. 129.

[8] L. T. Wang, K. Iiyama, F. Tsukada, N. Yoshida, and K. Hayashi, “Loss measurement in optical waveguide devices by coherent frequency-modulated continuous-wave reflectometry.,” *Opt. Lett.*, vol. 18, no. 13, p. 1095, 1993.

[9] U. Glombitza and E. Brinkmeyer, “Coherent Frequency-Domain Reflectometry for Characterization of Single-Mode Integrated-Optical Waveguide,” *J. Light. Technol.*, vol. 11, no. 8, pp. 1377–1384, 1993.

[10] Z. Jesse, *Optical Frequency Modulated Continuous Wave (FMCW) Interferometry*. Springer Science & Business, 2005.

[11] M. Song and S. Yin, “High-resolution LASER Chip Measurement Using Quadrature,” *Microw. Opt. Technol. Lett.*, vol. 23, no. 6, pp. 335–337, 1999.

[12] K. Iiyama, L. Wang, and K. Hayashi, “Linearizing Optical Frequency-Sweep of a Laser Diode for FMCW Reflectometry,” *J. Light. Technol.*, vol. 14, no. 2, pp. 173–178, 1996.

[13] S. Jung, S. R. Lee, and C. Park, "Correction of Nonlinear Frequency Sweep in Frequency-Modulated Continuous-Wave Laser Range Sensor," vol. 2013, 2013.

[14] A. Lazam, A. Igarashi, N. Atsushi, T. Maruyama, and K. Iiyama, "Linearizing optical frequency sweep of a DFB laser by modulation waveform optimization for high resolution FMCW sensing system," *Int. J. Electr. Electron. Res.*, vol. 5, no. 6, pp. 1–10, 2015.

[15] Nathaniel Joseph C. Libatique, "Tunable infrared laser sources and applications," 2002.

[16] L. Rovati and U. Minoni, "Analog Signal Pre-Processing for Performance Enhancement of a Distance Meter Based on Frequency-Modulated Continuous-Wave Interferometry," *IEEE Instrum. Meas.*, pp. 1141–1144, 1998.

[17] P. M. B. S. Girao, O. a Postolache, J. a B. Faria, and J. M. C. D. Pereira, "An Overview and a Contribution to the Optical Measurement of Linear Displacement," *IEEE Sens. J.*, vol. 1, no. 4, pp. 322–331, 2001.

[18] J. Graeme, *Photodiode amplifiers*. McGraw-Hill, 1996.

[19] J. L. Hall, "Optical frequency measurement: 40 years of technology revolutions," *Sel. Top. Quantum Electron. IEEE J.*, vol. 6, no. 6, pp. 1136–1144, 2000.

[20] Y. D. Bo Wu, "Narrow Linewidth Fiber Grating F-P Cavity Laser and Application," in *ieee explore*, 2009, vol. 00, pp. 1971–1974.

[21] F. J. Duarte, *Tunable Laser handbook*. Academic Press, 1995.

[22] M. Rioux, F. Blais, J. a Beraldin, and P. Boulanger, "Range imaging sensors development at {NRC Laboratories}," *Proc. IEEE Work. Interpret. 3D Scenes*, pp. 154–160, 1989.

[23] D. Nordin, "Optical Frequency Modulated Continuous Wave (FMCW) Range and Velocity Measurements," 2004.

[24] A. Rostami, M. Noshad, H. Hedayati, and A. Ghanbari, "A Novel and High-Precision Optical Displacement Sensor," *IEEE Sens. J.*, vol. 7, no. 4, pp. 311–316, 2007.

[25] M. N. Dubrov, "Laser feedback and new principle of heterodyne interferometry," *LFNM*, no. July, pp. 92–95, 2006.

[26] K. Määtta, J. Kostamovaara, and R. Myllylä, "Profiling of hot surfaces by pulsed time-of-flight laser range finder techniques," *Appl. Opt.*, vol. 32, no. 27, pp. 5334–5347, 1993.

[27] Ernest G. Wolff, "Fundamentals of Optical Interferometry for Thermal Expansion Measurements," in *27th International Thermal Conductivity Conference and 15th International Thermal Expansion Symposium*, 2003.

[28] L. P. Yatsenko, B. W. Shore, and K. Bergmann, "Ranging and interferometry with a frequency shifted feedback laser," *Opt. Commun.*, vol. 242, no. 4–6, pp. 581–598, 2004.

[29] T. Bosch, "Laser ranging: a critical review of usual techniques for distance measurement," *Opt. Eng.*, vol. 40, no. 1, p. 10, 2001.

[30] J. Geng, C. Spiegelberg, and S. Jiang, "Narrow linewidth fiber laser for 100-km optical frequency domain reflectometry," *Photonics Technol. Lett. …*, vol. 17, no. 9, pp. 1827–1829, 2005.

[31] B. Soller, D. Gifford, M. Wolfe, and M. Froggatt, "High resolution optical frequency domain reflectometry for characterization of components and assemblies.," *Opt. Express*, vol. 13, no. 2, pp. 666–674, 2005.

[32] K. Yüksel, M. Wuilpart, and P. Mégret, "Experimental investigations of coherent optical-frequency domain reflectometry," pp. 31–34, 2008.

[33] A. Kohlhaas, C. Fromchen, and E. Brinkmeyer, "High-resolution OCDR for testing integrated-optical waveguides: Dispersion-corrupted experimental data corrected by a numerical algorithm," *Journal of Lightwave Technology*, vol. 9, no. 11. pp. 1493–1502, 1991.

[34] P. Beaud, J. Schutz, W. Hodel, H. P. Weber, H. H. Gilgen, and R. P. Salathe, "Optical reflectometry with micrometer resolution for the investigation of integrated optical devices.," *IEEE J. Quantum Electron.*, vol. 25, no. 4, pp. 755–759, 1989.

[35] P. J. Urban, A. Getaneh, J. P. Von Der Weid, G. P. Temporão, and J. Chen, "Detection of Fiber Faults in Passive Optical Networks," *Opt. Commun. Netw.*, vol. 5, no. 11, pp. 1111–1121, 2013.

[36] M. Tateda and T. Horiguchi, "Advances in Optical Time-Domain Reflectometry," *J. Light. Technol.*, vol. 7, no. 8, pp. 1217–1224, 1989.

[37] M. K. Barnoski and S. D. Personick, "Measurements in Fiber Optics," *Proc. IEEE*, vol. 66, no. 4, pp. 429–441, 1978.

[38] M. M. Ibrahim and M. H. Ahmed, "Spectral analysis of a sampling optical time-domain reflectometer," *IEEE Trans. Instrum. Meas.*, vol. 37, no. 3, pp. 454–457, 1988.

[39] S. Y. G. Tai Yu Ren, "Development and characterization of tunable laser based optical time domain reflectometer," *hotonics (ICP),IEEE 2nd Int. Conf.*, 2011.

[40] I. a N. a White, J. F. Kuhl, and D. a N. L. Philen, "Single-Mode Fiber OTDR : Experiment and Theory," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-30, no. 10, 1982.

[41] C. It, "Optical Time Domain reflectometer with a semiconductor laser," *Electron. Lett.*, vol. 20, no. 18, pp. 714–716, 1984.

[42] G. Ripamonti, M. Ghioni, and A. Lacaita, "No Dead-Space Optical Time-Domain Reflectometer," *J. Light. Technol.*, vol. 8, no. 9, pp. 1278–1283, 1990.

[43] D. M. Baney and W. V. Sorin, “Extended-range optical low-coherence reflectometry using a recirculating delay technique,” *IEEE Photonics Technol. Lett.*, vol. 5, no. 9, pp. 1109–1112, 1993.

[44] G. Beheim, “Remote displacement measurement using a passive interferometer with a fiber-optic link,” *Appl. Opt.*, vol. 24, no. 15, pp. 2335–2340, 1985.

[45] J. Pluciński, R. Hypszer, P. Wierzba, M. Strąkowski, M. Maciejewski, and B. B. Kosmowski, “Optical low-coherence interferometry for selected technical applications,” *Bull. Polish Acad. Sci. Tech.*, vol. 56, no. 2, pp. 155–172, 2008.

[46] J. Yuan, C. Zhao, M. Ye, J. Kang, Z. Zhang, and S. Jin, “A Fresnel reflection-based optical fiber sensor system for remote refractive index measurement using an OTDR,” *Photonic Sensors*, vol. 4, no. 1, pp. 48–52, 2014.

[47] M. Wegmuller, P. Oberson, J. P. von der Weid, O. Guinnard, L. Guinnard, C. Vinegoni, M. Legre, and N. Gisin, “Overview of coherent reflectometry techniques: characterization of components and small systems,” *Tech. Dig. Symp. Opt. Fiber Meas. 2000 (NIST SP 953)*, pp. 155–60|viii+189, 2000.

[48] R. Passy, N. Gisin, J. P. Von Der Weid, and H. H. Gilgen, “Experimental and theoretical investigations of coherent OFDR with nsemiconductor laser sources,” *J. Light. Technol.*, vol. 12, no. 9, pp. 1622–1630, 1994.

[49] R. a Akhtiamov, V. F. Gusev, R. G. Zalyalov, G. a Morozov, O. G. Morozov, and V. M. Petoukhov, “Fiber optical frequency domain reflectometer,” in *Proceedings of 9th 1999: International CriMiCo’99*, 1999, no. September, pp. 352–353.

[50] R. 1. MacDonald, “Frequency domain optical reflectometer,” *Appl. Opt.*, vol. 20, no. 10, pp. 1840–1844, 1981.

[51] Yang Du, Tiegen Liu, Zhenyang Ding, Bowen Feng, Xiaobo Li, Kun Liu, and Junfeng Jiang, “Method for Improving Spatial Resolution and Amplitude by Optimized Deskew Filter in Long-Range OFDR,” *IEEE Photonics J.*, vol. 6, no. 5, pp. 1–11, 2014.

[52] A. Kanno and T. Kawanishi, “Broadband Frequency-Modulated Continuous-Wave,” *J. Light. Technol.*, vol. 32, no. 20, pp. 3566–3572, 2014.

[53] K. Tsuji, K. Shimizu, T. Horiguchi, and Y. Koyamada, “Coherent Optical Frequency Domain Reflectometry for a Long Single-Mode Optical Fiber Using a Coherent Lightwave Source and an External Phase Modulator,” *IEEE Photonics Technol. Lett.*, vol. 7, no. 7, pp. 804–806, 1995.

[54] B. Huttner, J. Reecht, N. Gisin, R. Passy, and J. P. Von Der Weid, “Local birefringence measurements in single-mode fibers with coherent optical frequency-domain reflectometry,” *IEEE Photonics Technol. Lett.*, vol. 10, no. 10, pp. 1458–1460, 1998.

[55] W. Li and X. Bao, “High Spatial Resolution Distributed Fiber Optic Technique for Strain and Temperature Measurements in Concrete Structures,” in *Canada 2013Conference*, 2013, pp. 1–11.

[56] Z. Ding, X. S. Yao, T. Liu, Y. Du, K. Liu, Q. Han, Z. Meng, J. Jiang, and H. Chen, "Long Measurement Range OFDR Beyond Laser Coherence Length," *IEEE Photonics Technol. Lett.*, vol. 25, no. 2, pp. 202–205, 2013.

[57] S. Venkatesh and W. V. Sorin, "Phase noise considerations in coherent optical FMCW reflectometry," *J. Light. Technol.*, vol. 11, pp. 1694–1700, 1993.

[58] P. Oberson, B. Huttner, O. Guinnard, L. Guinnard, G. Ribordy, and N. Gisin, "Optical frequency domain reflectometry with a narrow linewidth fiber laser," *Photonics Technol. Lett. IEEE*, vol. 12, no. 7, pp. 867–869, 2000.

[59] W. V Sorin, D. K. Donald, S. a Newton, and M. Nazarathy, "Coherent FMCW reflectometry using a temperature tuned Nd:YAG ring laser," *Photonics Technology Letters, IEEE*, vol. 2, no. 12. pp. 902–904, 1990.

[60] D. Uttam and B. Culshaw, "Precision time domain reflectometry in optical fiber systems using a frequency modulated continuous wave ranging technique," *J. Light. Technol.*, vol. 3, no. 5, pp. 971–977, 1985.

[61] J. Zheng, *Optical frequency-modulated continuous-wave (FMCW) interferometry*. Springer, 2005.

[62] W. Jiang, S. R. Pennock, and P. R. Shepherd, "FMCW Radar Range Performance Improvement With Modified Adaptive Sampling Method," *IEEE Geosci. Remote Sens. Lett.*, vol. 9, no. 4, pp. 668–671, 2012.

[63] J. Lorenzo, A. Lazaro, R. Villarino, D. Girbau, and S. Member, "Active Backscatter Transponder for FMCW Radar Applications," *IEEE Antennas Wirel. Propag. Lett.*, vol. 14, pp. 1610–1613, 2015.

[64] A. Anghel, G. Vasile, R. Cacoveanu, C. Ioana, and S. Ciochina, "Short-Range wideband FMCW radar for millimetric displacement measurements," *IEEE Trans. Geosci. Remote Sens.*, vol. 52, no. 9, pp. 5633–5642, 2014.

[65] I. Cnaan-on, S. Member, S. J. Thomas, J. L. Krolik, S. Member, M. S. Reynolds, and S. Member, "Multichannel Backscatter Communication and Ranging for Distributed Sensing With an FMCW Radar," *IEEE Trans. Microw. Theory Tech.*, vol. 63, no. 7, pp. 2375–2383, 2015.

[66] a. J. Hymans and J. Lait, "Analysis of a frequency-modulated continuous-wave ranging system," *Proc. IEE Part B Electron. Commun. Eng.*, vol. 107, no. 34, p. 365, 1960.

[67] R. a. Perez-Herrera, D. a. Pereira, O. Frazão, J. M. Castro Ferreira, J. L. Santos, F. M. Araújo, L. a. Ferreira, J. M. Baptista, and M. Lopez-Amo, "Optimization of the frequency-modulated continuous wave technique for referencing and multiplexing intensity-based fiber optic sensors," *Elselvier*, vol. 44, no. 1, pp. 230–237, 2011.

[68] A. Canagasabey, A. Michie, J. Canning, J. Holdsworth, S. Fleming, H. Wang, and M. L. Åslund, "A Comparison of Michelson and Mach-Zehnder Interferometers for Laser

Linewidth Measurements," in *IQEC/CLEO Pacific Rim*, 2011, vol. 1, no. September, pp. 1392–1394.

[69] R. a Perez-Herrera, O. Frazao, J. L. Santos, F. M. Araujo, L. a Ferreira, J. M. Baptista, and M. Lopez-Amo, "Frequency Modulated Continuous Wave System for Optical Fiber Intensity Sensors With Optical Amplification," *IEEE Sens. J.*, vol. 9, no. 12, pp. 1647–1653, 2009.

[70] P. K. C. K. C. Chan, W. Jin, J. M. M. Gong, and N. S. S. Demokan, "Multiplexing of fiber Bragg grating sensors using a FMCW technique," *IEEE Photonics Technol. Lett.*, vol. 11, no. 11, pp. 1470–1472, 1999.

[71] J. Zheng, "Differential birefringent fiber frequency-modulated continuous-wave sagnac gyroscope," *Photonics Technol. Lett.*, vol. 17, no. 7, pp. 1498–1500, 2005.

[72] G. Morthier and P. Vankwikelberge, *Handbook of distributed feedback laser diodes*, Secend Edi. Artech House, 2013.

[73] E. D. Moore and R. R. McLeod, "Correction of sampling errors due to laser tuning rate fluctuations in swept-wavelength interferometry.," *Opt. Express*, vol. 16, no. 17, pp. 13139–13149, 2008.

[74] E. B. Li, a K. Tieu, and K. F. Wang, "Dynamic laser speckle method for determining the relative velocity between two objects," *Opt. Commun.*, vol. 219, no. 1–6, pp. 1–8, 2003.

[75] L.-T. Wang, K. Liyama, and K.-I. Hayashi, "A study on degradation of spatial resolution in frequency-modulated continuous wave reflectometry due to nonlinear optical frequency sweep," *Electron. Commun. Japan (Part II Electron.*, vol. 78, no. 10, pp. 28–35, 1995.

[76] D. King, W. B. Lyons, C. Flanagan, and E. Lewis, "A multipoint optical fibre sensor system for use in process water systems based on artificial neural network pattern recognition techniques," *Sensors Actuators A Phys.*, vol. 115, no. 2–3, pp. 293–302, 2004.

[77] I. P. G. Brian Culshaw, "Frequency Modulated Heterodyne Sagnac Interferometer," *IEEE Trans. Microw. Theory Tech.*, vol. VOL. MTT-3, pp. 536–539, 1982.

[78] K. Iiyama, M. Yasuda, and S. Takamiya, "Extended-Range High-Resolution FMCW Reflectometry by Means of Electronically Frequency-Multiplied Sampling Signal Generated from Auxiliary Interferometer," *IEICE Trans. ElectronScience*, no. 6, pp. 823–829, 2006.

[79] K. Iiyama, S. I. Matsui, T. Kobayashi, and T. Maruyama, "High-resolution FMCW reflectometry using a single-mode vertical-cavity surface-emitting laser," *IEEE Photonics Technol. Lett.*, vol. 23, no. 11, pp. 703–705, 2011.

[80] K. Iiyama, L. T. Wang, and K. I. Hayashi, "Linearizing optical frequency-sweep of a laser diode for FMCW reflectometry," *J. Light. Technol.*, vol. 14, pp. 173–177, 1996.

[81] M. Lu, H.-C. Park, J. S. Parker, E. Bloch, A. Sivananthan, Z. Griffith, L. a. Johansson, M. J. Rodwell, and L. a. Coldren, “A Heterodyne Optical Phase-locked Loop for Multiple Applications,” *Opt. Fiber Commun. Conf. Fiber Opt. Eng. Conf. 2013*, p. OW3D.1, 2013.

[82] K. Takada, “High-Resolution OFDR with Incorporated Fiber-optic Frequency Encoder,” *IEEE Photonics Technol. Lett.*, vol. 4, no. 9, pp. 1069–1072, 1992.

[83] P. K. C. Chan, W. Jin, S. Member, and M. S. Demokan, “FMCW Multiplexing of Fiber Bragg Grating Sensors,” *Quantum Electron.*, vol. 6, no. 5, pp. 756–763, 2000.